M.L. 2018, Chp. 214, Art. 4, Sec. 02, Subd. 04c as extended by M.L. 2021, First Special Session, Chp. 6, Art. 6, Sec. 2, Subd. 18 Project Abstract
For the Period Ending June 30, 2022

PROJECT TITLE: Reduce Chlorides in Minnesota Waters by Evaluating Road-Salt Alternatives and Pavement Innovations
PROJECT MANAGER: John S. Gulliver
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FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2018, Chp. 214, Art. 4, Sec. 02, Subd. 04c as extended by M.L. 2021, First Special Session, Chp. 6, Art. 6, Sec. 2, Subd. 18

APPROPRIATION AMOUNT: $400,000
AMOUNT SPENT: $400,000
AMOUNT REMAINING: $0

Sound bite of Project Outcomes and Results

This project produced background information, guidance and recommendations on the benefits and consequences of chloride-based road salt and non-chloride alternatives for de-icing and anti-icing Minnesota's roadways, which will assist road maintenance decision makers in reducing pollution from winter road management.

Overall Project Outcome and Results

Over 100,000 tons of road salt are applied to Minnesota's roads each year to prevent or reduce snow and ice cover during the winter season. Sodium chloride is typically used because it is inexpensive and effective, but it can corrode vehicles, pavement, and metal structures (e.g., bridges), and it increases chloride concentration in surface and ground waters throughout the state. This results in additional costs for replacing roadway infrastructure and reduces water quality, habitat, and biodiversity in our natural resources. This project investigated alternatives to sodium chloride-based road salt that reduce snow and ice on roadways with less environmental impact. The project team reviewed scientific research papers, performed laboratory experiments, and used computer models to predict the potential environmental impacts of these chemicals on Minnesota's natural resources.

This project found several outcomes, including: 1) chloride-based road salt concentration can exceed the chronic and acute water quality standards during a typical year; 2) acetate-based alternatives only exceeded water quality standards for low flow rates (low dilution); 3) potassium-based chemicals can be toxic at low concentration, and toxicity thresholds are exceeded when potassium is applied over all roadways for all winter storms; 4) other alternatives such as formate, glycol, glycerol, and succinate have varying performance, application rate, and toxicity thresholds; 5) water-heated sand improves friction compared to bare ice or dry sand on bare ice and can be removed from the environment with simple grit collection chambers; and 6) non-chloride alternatives can reduce the bonding strength of ice to a solid surface. Thus, water-heated sand as an abrasive and organic or hydrophobic non-chloride alternatives can be used to reduce the use of chloride-based road salt and provide more winter benefit on Minnesota's roadways, but modeling predicts that some of these chemicals could exceed toxicity thresholds if applied for all conditions.

Project Results Use and Dissemination

The results from this project have been shared via presentations, interviews, reports, academic journals, and with stakeholders and decision makers during conferences and networking events. Some examples include a web article, two invited annual Minnesota Salt Symposium presentations (2019 & 2021), WCCO's 10 o'clock news "Good Question: How Does Salt Melt Ice?" with Jeff Wagner, the Transportation Research Board Annual meeting (2022), and several conference presentations and professional meetings. We believe sharing this information has enlightened decisions makers about the dangers of chloride road salts and non-chloride alternatives and how best to use each.

Environment and Natural Resources Trust Fund (ENRTF) M.L. 2018 ENRTF Work Plan Final Report

Today's Date: August 15, 2022

Final Report

Date of Work Plan Approval: June 5, 2018

Project Completion Date: June 30, 2022

PROJECT TITLE: Reduce Chlorides in Minnesota Waters by Evaluating Road-Salt Alternatives and Pavement Innovations

Project Manager: John S. Gulliver

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Location: Statewide

Total Project Budget: $400,000

Amount Spent: $400,000

Balance: $0

Legal Citation: M.L. 2018, Chp. 214, Art. 4, Sec. 02, Subd. 04c as extended by M.L. 2021, First Special Session, Chp. 6, Art. 6, Sec. 2, Subd. 18

Appropriation Language: $400,000 the second year is from the trust fund to the Board of Regents of the University of Minnesota to investigate road-salt alternatives and pavement innovations to reduce lake, stream, and groundwater degradation caused by road-salt chlorides. This appropriation is available until June 30, 2021, by which time the project must be completed and final products delivered.

M.L. 2021, First Special Session, Chp. 6, Art. 6, Sec. 2, Subd. 18. ENVIRONMENT AND NATURAL RESOURCES TRUST FUND; EXTENSIONS. [to June 30, 2022]

I. PROJECT STATEMENT:

This project will investigate road salt alternatives and pavement innovations that will reduce or eliminate the high flux of chloride from road salt into our environment and thus improve the water quality of our lakes, streams and groundwater.

Road salt impacts water quality, and will be a primary 21st century pollutant of concern in northern regions. Minnesota annually uses ~90 lbs per person of road salt (sodium chloride) to de-ice our roads and parking lots. Most of the sodium is trapped by the soil, but chloride is washed off of the streets or will move through the soil to receiving water bodies. We know from previous research that salt is accumulating to toxic levels in many lakes, streams and shallow groundwater. In the Twin Cities metropolitan area, for example, there are already 26 impaired lakes, 23 impaired streams and 1 impaired wetland for chloride. There is a strong possibility that lakes in urban Minnesota will become unable to support some of their fresh water organisms. Road salt alternatives and pavement innovations have the potential to provide similar road friction conditions while having less impact on the environment. We need to investigate the cost-effective application of these alternatives and pavement innovations now, to prepare for the near-future when a substitute for road salt is desired and needed.

The outcome of this project is to investigate and enhance strategies that improve water quality by evaluating road salt alternatives and pavement innovations to reduce the chloride load from road runoff. The methods and tools developed during this project will inform state, municipal and private entities using chloride –based salt on roads and parking lots. A feasibility matrix will be developed to summarize high level economic, environmental, time frame, implementation & maintenance challenges and benefits for alternate strategies.

A better understanding of road friction for road salt alternatives, combined with knowledge of environmental impacts and application and infrastructure costs will enable an improved decision-making process for public and private entities. City, county and MnDOT engineers will soon be making decisions about the best road salt alternative for their application. In addition, commercial entities are salting parking lots to reduce liability. This research could be used by the legislature to limit this liability if proper practices are used. The need for this research and the information it will generate is great, and the timing is urgent.

Input and advice from several agencies will be utilized to ensure that the goals of this research are met, and that the findings are useful to, and shared with, decision-makers in Minnesota. First, we have partnered with the Minnesota Pollution Control Agency (Brooke Asleson) for many years on the impacts of road salt. Second, we have enlisted the assistance of the Minnesota Department of Transportation (Steven Lund), who directs the maintenance and operation unit of the Metro District. Finally, we will seek advice from the members of the Stormwater Research Council, who participate and are involved in much of the stormwater research in Minnesota.

II. OVERALL PROJECT STATUS UPDATES:

First Update January 31, 2019

The project team has met several times to discuss the activities and outcomes. The literature review is complete and is submitted with this project update. Effort towards the modeling and friction measurements have commenced.

Second Update June 30, 2019

The project team has met several times to discuss the activities and outcomes. A meeting with modeling experts was held to discuss capabilities of various model software and applicability to modeling road salt alternative impacts. Several meetings with the staff coordinating the experiments (Activity 3) resulted in the development of two separate protocols for measuring de-icing and anti-icing effectiveness of various road salt alternatives. The road salt alternatives currently under consideration include conventional salt (NaCl) as a baseline for comparison, Magnesium Chloride ($MgCl_2$), Potassium Acetate (KAc), CF7 (commercial KAc mix), Propylene Glycol (organic chemical), Abrasives (de-icing only), and Pavement Technologies (pending availability).

Amendment Request (09/05/2019)
Re-budget for Lab Services, equipment, and lab supplies: We are requesting a re-budget of $5,900 to allow for laboratory analysis of samples. Additional analytical services are needed to analyze road-side soil samples to compare the presence of sodium and chloride (conventional road salt) and soil properties that could be used to model breakdown of road salt alternatives such as organic chemicals. The analytical services will be provided by the Research Analytical Laboratory on the St. Paul Campus of the University of Minnesota because they provide soil analysis at a reduced rate for University of Minnesota projects. The reduced rates allow for more samples to be analyzed for more parameters. In addition, a friction measurement device was available for loan from the MN Dept. of Transportation. Thus, the purchase of a British Pendulum Tester is no longer necessary. We are requesting that the cost for the pendulum tester ($9,000) be reallocated partially to pay for analytical services ($5,900) and the remainder added to Equipment/Tools/Supplies ($3,100). The additional funds for Equipment/Tools/Supplies will be used to expand the experiments to include measurement of adhesive strength of road salt alternatives. Many road salt alternatives are used as anti-icing to minimize adhesion of the snow and ice to the pavement, allowing for easier removal via plowing. These additional experiments will measure adhesive (shear) strength of ice to a surface in the presence of various road salt alternatives to simulate these real-world application techniques. Thus, the new budget for Equipment/Tools/Supplies is $18,100. These changes are shown in the expenditures spreadsheet.

Amendment Approved by LCCMR 10/09/2019.

Third Update January 31, 2020

The project team has met several times to discuss the activities and outcomes. Several alternatives were discussed, and it was determined that only a few alternatives are used or would be considered for use by the industry; Potassium Acetate (KAc) and propylene glycol. As a result, these chemicals have been recommended for laboratory testing and Activity 2, Outcome 2 is complete.

Amendment Request (01/31/2020)
In meeting with the team members for Activity 2 (modeling environmental impacts) and Activity 3 (measuring friction), we have determined that the data results from Activity 3 should be used to inform and improve the modeling effort in Activity 2. As a result, we request that the deadline for Activity 2, Outcome 1 be extended through the duration of Activity 3 (3/31/2021) so they can be completed concurrently. Activity 2, Outcome 2 is complete as described in the status update.

Amendment Approved by LCCMR 2/8/2020.

Laboratory testing (Activity 3) of anti-icing has continued, measuring the effect of sodium chloride, magnesium chloride, and potassium acetate at four temperatures (-5 °C, -15 °C, -25 °C, -35 °C).

Fourth Update June 30, 2020

The project team has met several times to discuss the activities and outcomes. During these discussions, it was hypothesized that a hydrophilic (water-repellent) substance could weaken the bond between ice and pavement, thus reducing the need for road salt. Thus, a commercial hydrophilic substance commonly used on vehicles (RainX) was added to the list of alternatives to be tested as part of this research.

Activity 2, Outcome 1 continues concurrently with Activity 3, Outcome 1. Computer modeling using EPA SWMM has the potential of modeling runoff, application of rock salt, NaCl-based brine, and potassium acetate. More detail is provided in the activity below. This software will be used to complete Activity 3, Outcome 1.

Laboratory testing (Activity 3) consists of friction measurements for de-icing and friction enhancement (e.g., sand and grit) and anti-icing experiments which measure the ability of road salt and road salt alternatives to weaken the bond between ice and pavement. All anti-icing chemicals that were planned for testing (no treatment, Na-Cl-based brine, Magnesium Chloride, Potassium Acetate, RainX) have been tested at various temperatures (-15 °C, -25 °C, -35 °C). Friction measurements for de-icing and friction enhancement will resume in the next biennium (July – Dec 2020).

Fifth Update January 31, 2021

We responded by email on October 6, 2020 that this project has experienced COVID- related delays that have resulted in a need for an extension to our project funding in order to complete the designated outcomes. We could not get into the University to perform laboratory experiments for some months, which set back the entire project, and were occupied by COVID -related arrangements for our other projects, so we would appreciate having some more time to complete the project. We were updated on December 6, 2020, that our project was included in the request to extend funding and that the status still in process.

Activity 2, Outcome 1 continues concurrently with Activity 3, Outcome 1. Computer modeling has shown that EPA SWMM can model runoff, application of rock salt, NaCl-based brine, and potassium acetate. More detail is provided in the activity below. This software will be used to complete Activity 2, Outcome 1. Upon completion of Outcome 1, Activity 2 will be complete. There has been progress on this activity, but we were delayed due to Covid-19 related time conflicts.

Laboratory testing (Activity 3) consists of friction measurements for de-icing and friction enhancement (e.g., sand and grit) and anti-icing experiments which measure the ability of road salt and road salt alternatives to weaken the bond between ice and pavement. Experimental data collection is tentatively complete and data analysis is underway. Activity 3, Outcome 1 was delayed due to Covid-19 related time and access conflicts. Pending data analysis approval, Activity 3, Outcome 1 will be complete during this biennium (Jan – June 2021). Subsequent to completion of Outcome 1, Outcome 2 (develop ranking metrics) and Outcome 3 (write report) can then be completed.

Project extended to June 30, 2022 by LCCMR 6/30/21 as a result of M.L. 2021, First Special Session, Chp. 6, Art. 6, Sec. 2, Subd. 18, legislative extension criteria being met.

Sixth Update June 30, 2021:

Activity 2, Outcome 1 continues concurrently with Activity 3, Outcome 1. EPA SWMM is currently being used to model runoff, application of rock salt, NaCl-based brine, and potassium acetate. More detail is provided in the activity below. This software is being used to complete Activity 2, Outcome 1.

Laboratory testing (Activity 3) consists of friction measurements for de-icing and friction enhancement (e.g., sand and grit) and anti-icing experiments which measure the ability of road salt and road salt alternatives to weaken the bond between ice and pavement. Experimental data collection and data analysis are complete. Report preparation for Activity 3 is underway.

Seventh Update January 31, 2022:

Activity 2, Outcome 1 continues concurrently with Activity 3, Outcome 1. EPA SWMM is continuing to be used to model transport of chloride-based road salt and potassium acetate as an alternative. Preliminary analysis from this effort, combined with results from a concurrent synergistic project funded by the MnDOT Local Road Research Board (LRRB), suggest that potassium (K) may have more environmental impacts than Acetate (Ac). This is because the toxicity limit of potassium was discovered to be substantially lower than the toxicity limit for acetate. The modeling and analysis are nearly complete and will be finished and written into the final report by the project end date of June 30, 2022.

Laboratory testing (Activity 3) consists of friction measurements for de-icing and friction enhancement (e.g., sand and grit) and anti-icing experiments which measure the ability of road salt and road salt alternatives to weaken the bond between ice and pavement. Experimental data collection and data analysis are complete. Two manuscripts describing the results have been prepared; one submitted for publication and a second manuscript will be completed and submitted for publication during this biennium.

The literature review (Activity 1), results from the modeling effort (Activity 2), and the manuscripts describing the laboratory testing (Activity 3) will be combined into the final report for this project and submitted by the project end date, June 30, 2022.

April 21, 2022 Amendment Request

An amendment to the budget is requested to shift funds in order to approach zero balance in each of the categories. Items which are completed will have extra funds shifted to items that have a negative balance or to items that are still in progress.

Amendment Approved by LCCMR 7/5/2022.

Final Update June 30, 2022

Activity 1: Literature review was completed early in the project and revised for inclusion in this final report and status update. Topics in the literature include: alternatives to chloride-based road salt (acetate-based, formate-based, glycol and glycerol, succinate-based, and other road salt alternatives), performance of road salt alternatives (RSAs), environmental impacts, abrasives, pavement innovations (Pavement Heating, Deicers in the Pavement Mix Design, Hydronic Pavements, Hydrophobic Pavements, and other pavement innovations), and observations and recommendations.

Activity 2: Investigate water quality impacts of RSAs in Minnesota was completed during the last biennium of the project. During the previous biennium, the results of a model assessment of environmental impacts of potassium acetate for the Miller Creek Watershed near Duluth, MN was presented. During the last biennium, other RSAs and climate regimes (when they should be applied) were considered. The primary differences between the environmental impacts of acetate and other RSAs include climate regime, application rate, decay rate coefficient, and toxicity thresholds for the chemicals being considered. These variables are discussed in this final report and status update. The best approach for assessing environmental impacts is for end users to choose the conditions for which they want the environmental impacts and model those conditions specifically, following the example established by this research project (see example in the Seventh Update (January 31, 2022) for Activity 2).

The experimental data collection and analysis for Activity 3: Conduct friction tests on pavement cores to select promising techniques was completed during the Sixth Update (June 30, 2021). The project team has drafted two manuscripts for publication in peer-reviewed journals describing the methods and results of these experiments. In summary, it was shown that 1) water-heated sand is an alternative to chloride-based road salt that can improve friction compared to bare ice or dry sand on bare ice, and 2) non-chloride RSAs can reduce the bonding strength of ice to a solid surface at colder temperatures. Thus, water-heated sand as an abrasive and organic or hydrophobic non-chloride RSAs can be used to reduce the use of chloride-based road salt and provide more winter benefit on Minnesota's roadways.

Overall Project Outcome and Results

Over 100,000 tons of road salt are applied to Minnesota's roads each year to prevent or reduce snow and ice cover during the winter season. Sodium chloride is typically used because it is inexpensive and effective, but it can corrode vehicles, pavement, and metal structures (e.g., bridges) and increases chloride concentration in surface and ground waters throughout the State. This results in additional costs for replacing roadway infrastructure and reduces water quality, habitat, and biodiversity in our natural resources. This project investigated alternatives to sodium chloride-based road salt that reduce snow and ice on roadways with less environmental impact. The project team reviewed scientific research papers, performed laboratory experiments, and used computer models to predict the potential environmental impacts of these chemicals on Minnesota's natural resources.

This project found several outcomes, including: 1) chloride-based road salt concentration can exceed the chronic and acute water quality standards during a typical year, 2) acetate-based alternatives only exceeded water quality standards for low flow rates (low dilution), 3) potassium-based chemicals can be toxic at low concentration and toxicity thresholds are exceeded when potassium is applied over all roadways for all winter storms, 4) other alternatives such as formate, glycol, glycerol, and succinate have varying performance, application rate, and toxicity thresholds, 5) water-heated sand improves friction compared to bare ice or dry sand on bare ice and can be removed from the environment with simple grit collection chambers, and 6) non-chloride alternatives can reduce the bonding strength of ice to a solid surface. Thus, water-heated sand as an abrasive and organic or hydrophobic non-chloride alternatives can be used to reduce the use of chloride-based road salt and provide more winter benefit on Minnesota's roadways, but modeling predicts that some of these chemicals could exceed toxicity thresholds if applied for all conditions.

III. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: Synthesize past and current investigations.
Description: Past and current investigations of road salt alternatives, pavement innovations and road friction studies will be reviewed. We are aware that there are substantial research needs here and that sufficient information will not be available for all alternatives, but this review will limit duplication of effort and maximize progress towards essential knowledge gaps.

ENRTF BUDGET: $27,596

Outcome	Completion Date
1. Synthesize past and current investigations	12/31/2018

Final Update January 31, 2019
The literature review is complete and is submitted with this project update.

ACTIVITY 2: Investigate water quality impacts of road salt alternatives in Minnesota.
Description: Information gathered in Activity 1 will be synthesized through the use of computer models to evaluate potential water quality impacts of road salt alternatives in Minnesota. Many of the non-chloride-based alternatives are organic compounds, which have a biological oxygen demand when released into the

environment. The amount of such alternatives required for anti-icing and de-icing will be estimated from literature values, and computer models will then be used to determine the water quality impacts of these amounts on common water resources in Minnesota.

ENRTF BUDGET: $181,670

Outcome	Completion Date
1. Predict water quality impacts in Minnesota for alternatives	03/31/2021
2. Select alternatives for laboratory testing	12/31/2019

First Update January 31, 2019

The literature review provided input into the available models and past studies on the impact of road alternatives or similar organic chemicals on the environment. Modelling will commence in the next semi-annual period.

Second Update June 30, 2019

A meeting with modeling experts was held to discuss capabilities of various model software and applicability to modeling road salt alternative impacts. It was determined that a simple model and open source model is best for accessibility to various groups and industry professionals, but a more complex model may be used for calibration and comparison of impacts at different locations.

Third Update January 31, 2020

In reviewing the literature, talking with industry professionals, and discussing the options with the project team (modeling and experiments), it was determined that there are only a few road salt alternatives that are used or would be considered for use by the industry. The existing chloride-based road salts include NaCl and MgCl2. The alternatives include Potassium Acetate (KAc) and propylene glycol. These alternatives will be modeled (Activity 2) and are recommended for laboratory testing (Activity 3) as part of this project. Thus, Outcome 2 is complete.

Meetings with modeling experts were held to discuss use of various model software to predict environmental impacts of road salt alternative impacts. The project team agreed that a simple and open source model will be developed for industry professionals and the more complex model will be improved by using information from Activity 3 to calibrate and verify the model to predict the environmental impacts at different locations. With the proposed amendment request (see above), outcome 1 of this activity would continue throughout the duration of Activity 3 to improve the outcomes for the entire project.

Fourth Update June 30, 2020

Activity 2, Outcome 1 continues concurrently with Activity 3, Outcome 1. EPA-SWMM has the capabilities to model snowfall, snow plowing, snowmelt, and KAc transport and decay. In addition, EPA-SWMM is freely accessible (https://www.epa.gov/water-research/storm-water-management-model-swmm) and commonly used by County, and City staff in Minnesota. This software will be used to complete Activity 3, Outcome 1. So far, rock salt (solid NaCl), salt brine (liquid NaCl & $MgCl_2$), and Potassium Acetate (liquid KAc) has been modeled using EPA-SWMM on an example watershed, as shown in Figure 1.

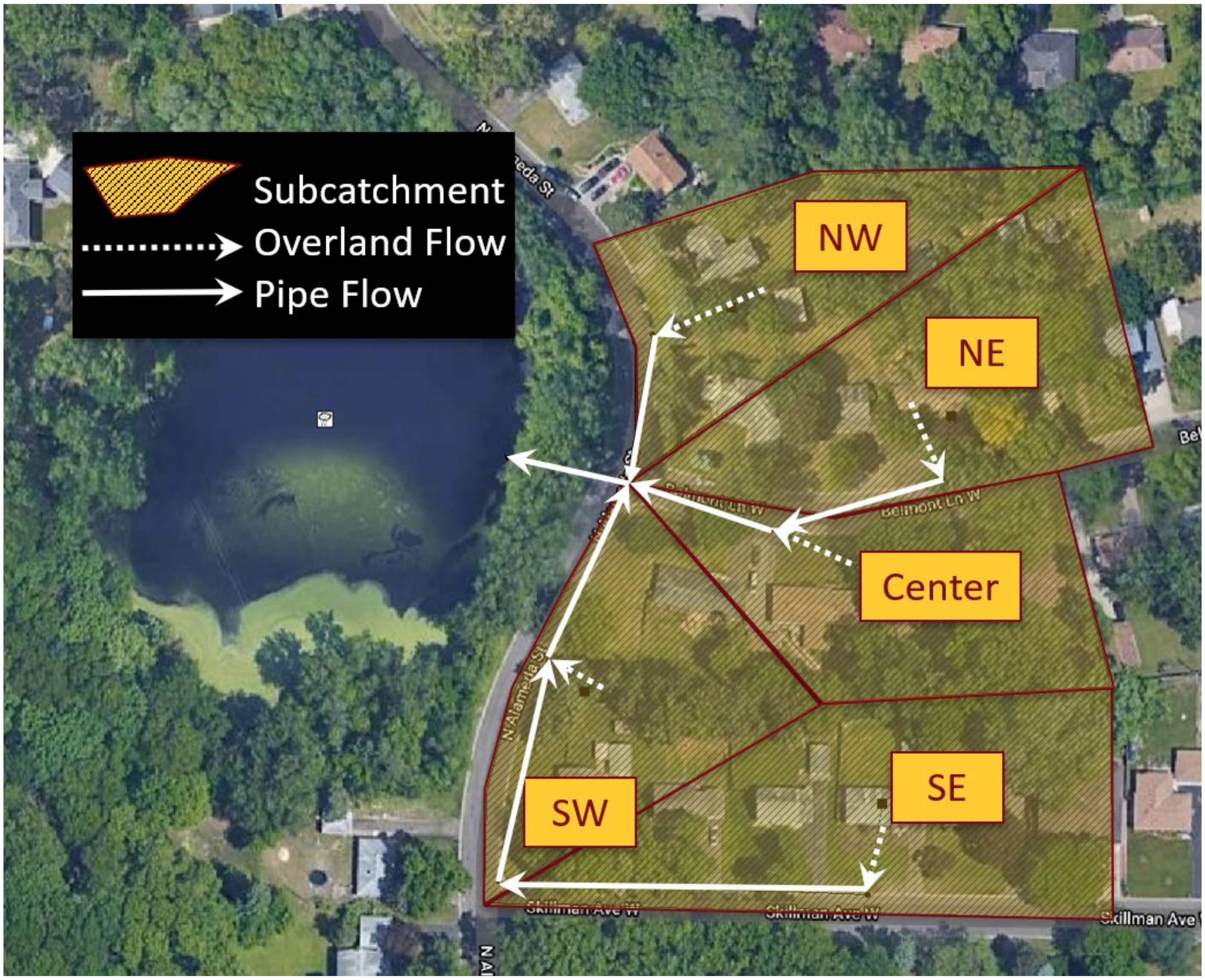

Figure 1: Schematic of hypothetical urban subwatershed modeled in EPA-SWMM.

EPA-SWMM was used to predict the response of a hypothetical scenario which spanned a period of 11 days with three precipitation events on days 2, 6, and 9 with total cumulative snowfalls of 125 mm (4.9 inches), 50 mm (1.97 inches), and 50 mm (1.97 inches), respectively. The temperature record was represented by a sinusoidal diurnal cycle with a max temperature of +15°C and a minimum temperature of -5°C. The climate data, unit area runoff (mm/hr), and maximum snow depth (mm) are shown in Figure 2. EPA-SWMM also transports snow from impervious surfaces (roadways) to pervious surfaces (lawns and ditches) in addition to snow accumulation, melt, and runoff (data now shown).

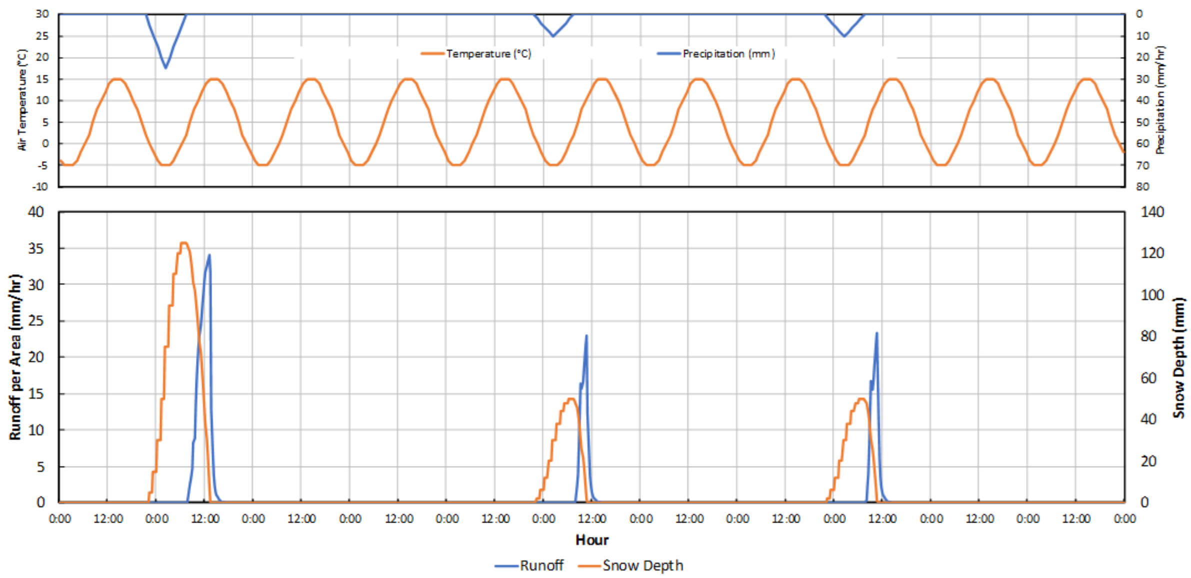

Figure 2: Simulated climate, runoff, and max snow depth for hypothetical watershed modeled by EPA-SWMM.

Pollutant fate and transport was simulated using SWMM for multiple deicers, including Rock salt (solid NaCl), liquid brine (NaCl and $MgCl_2$, separately) and Potassium Acetate (KAc). The application rates in this hypothetical scenario were as follows:

- NaCl Rock Salt: 500 lbs / lane mile NaCl ≈ 85,486 mg Cl- per m of curb (mg/L as Cl^-)
- NaCl Brine: 30 gal / lane mile @ 23.3% by mass ≈ 9,973 mg Cl- per m of curb (mg/L as Cl^-)
- MgCl2 Brine: 20 gal / lane mile @ 21.6% by mass ≈ 7,568 mg Cl- per m of (mg/L as Cl^-)
- KAc Liquid: 42.5 gal / lane mile @ 49% by mass ≈ 29,468 mg Ac- per m of curb (mg/L as Ac^-).

The pollutant fate and transport results from this hypothetical scenario are illustrated in Figure 3. The peak runoff concentration for each pollutant corresponds proportionally with the application rate described above. As expected, the rock salt application (≈ 85,486 mg Cl- per m of curb) produced considerably higher runoff concentration than the liquid-applied chemicals. The runoff concentration, however, did not vary based on the event size. We suspect this is because the model is applying the chemicals based on duration of the event and not based on the amount of snowfall during the event. Additional testing is needed to confirm this hypothesis and how to apply the chemicals to accurately represent application practices in industry. The pollutant transport is otherwise as expected.

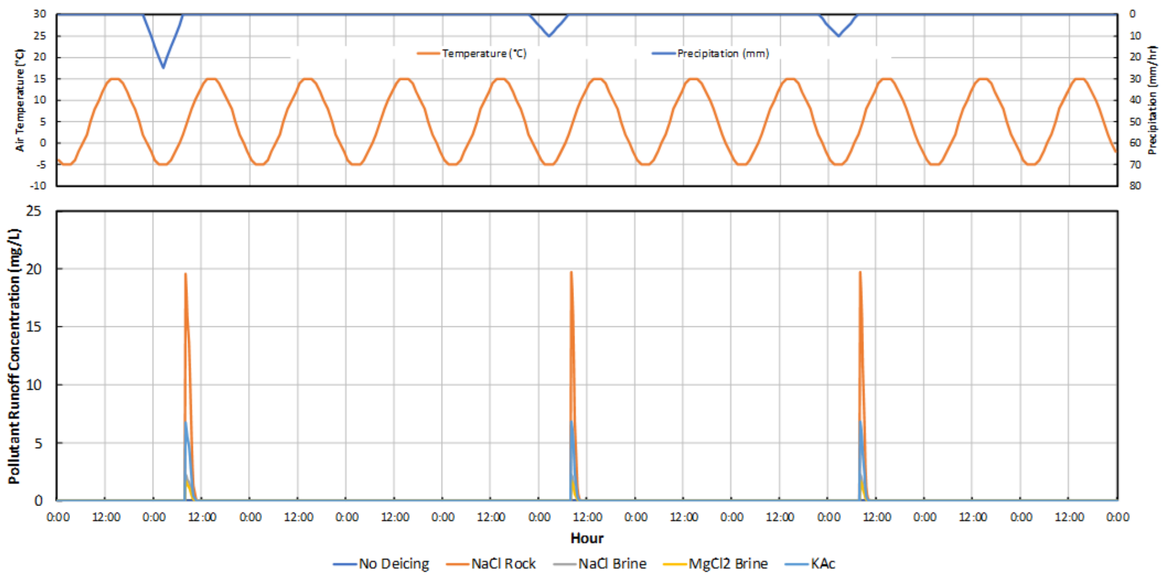

Figure 3: Pollutant runoff concentration (mg/L) for rock salt, liquid brine (NaCl and MgCl2), and potassium acetate (KAc).

Finally, the transport of potassium acetate (KAc) also requires natural biodegradation of KAc in the environment during transport. This can be modeled within EPA-SWMM using the built-in first order decay rate equation or a user-defined decay process. The first-order decay rate equation was tested and found to function within EPA-SWMM as expected (results not shown). Values for first-order decay based on temperature for KAc will be assumed from literature values and used to calibrate the model to accurately model biodegradation of KAc. Other road salt alternatives, such as propylene glycol, will also be investigated and incorporated into the model if the appropriate modeling parameters are available to input in EPA-SWMM. This will be completed throughout the remainder of the project.

Fifth Update January 31, 2021

Three EPA-SWMM models that represent different regions in Minnesota have been selected to demonstrate the environmental impacts of road salt and road salt alternatives. These models including Miller Creek watershed, encompassing portions of Hermantown and Duluth, MN in the Toimi Drumlins and North Shore Highlands ecoregions. The Miller Creek watershed and model covers approximately 10 square miles, originating in the headwaters of Miller Creek in Hermantown and discharging into Lake Superior at 26th Ave. West in Duluth, just below Lincoln Park. The unique features of this model are the combination of undeveloped rural landscapes, developing areas, and fully-built areas such as downtown Duluth, shallow bedrock and clay subsoils, and a substantial elevation change of about 760 feet.

The second model selected to represent Minnesota is a portion of the City of Minneapolis, MN, which lies within the St. Croix Outwash Plain and Stagnation Plain ecoregion. This model will reflect ultra-urban, fully developed metropolitan areas throughout MN. The third model selected to represent Minnesota is located northwest of Rochester, MN and encompasses approximately 7.5 square miles within the Rochester/Paleozoic Plateau Upland ecoregion. The unique features of this model are the combination of undeveloped rural landscapes, developing areas, and fully-developed residential areas, karst geology, and a relatively flat topography.

These models will be used to assess the environmental impacts of road salt (e.g., NaCl, $MgCl_2$, $CaCl_2$) and road salt alternatives (e.g., K-Acetate, propylene glycol) as discussed in the previous status report (Jan – Jun 2020). Sensitivity analysis began during the current biennium (Jul – Dec 2020) but will be complete in the next biennium (Jan – Jun 2021). The sensitivity analysis will illuminate which input parameters (e.g., application rate, biodegradation rate, hydraulic residence time) are most important for predicting environmental impacts. When sensitivity analysis is complete, then the models can be used to predict the environmental impacts based on various input conditions. The result of this modelling effort will be thresholds of road salt alternatives application rates at which environmental impacts are significant.

Sixth Update June 30, 2021:

The Miller Creek model in the Duluth region is proceeding well. We are expanding this project with the help of a Minnesota Department of Transportation project to study the impacts of potassium acetate on the environment in MnDOT Region 1, when applied as a road salt anti-icing alternative. We will model the environmental impacts of propylene glycol as well, which is not part of the MnDOT project.

We have had some challenges with currently selected inputs for the Minneapolis region and Rochester region models. Neither of the models had the objective of constituent transport, so their calibration criteria were dissimilar to ours. We have had to recalibrate the models, which is requiring some time. Calibration of the models is occurring currently.

Seventh Update January 31, 2022:

Full modeling details and results will be provided in the final report. The following is a synopsis of some of the results.

1 Scenario Analysis of Environmental Impacts of Potassium Acetate

The Miller Creek EPA-SWMM Model was used to model the environmental impacts from an individual subcatchment and from a tributary watershed in various potassium acetate (KAc) application scenarios. First, EPA-SWMM was used to model the runoff and outflow concentration of K and Ac from an individual subcatchment. It was hypothesized that runoff from some individual subcatchments could contain large concentrations of K and Ac due to high application rates and lack of dilution prior to entering receiving waters. It was also hypothesized that the concentration would be less within Miller Creek and in the outflow from Miller Creek due to dilution by the creek and contributions from other subcatchments with lesser anti-icer application rates. The results from these simulations are described in the following sections. All model runs simulated runoff and pollutant concentration using the above-mentioned model parameters and precipitation data from November 1, 1998 to April 30, 1999.

1.1 Runoff and Outflow Concentration from an Individual Subcatchment

The Miller Creek EPA-SWMM model was used to simulate runoff and K and Ac concentrations in the outflow from a single subcatchment (12.8 acres) when KAc application was assumed on all roadways. For the period of November 1, 1998 to April 30, 1999 (close to a median total snowfall for the last 30 years of record) there were 1023 hours of non-zero runoff values (Q) ranging from 0.01 cfs to 1.23 cfs. This data was sorted from smallest to largest flow rate and the percent exceedance (Erickson et al. 2013) was calculated and plotted as shown in Figure 4.

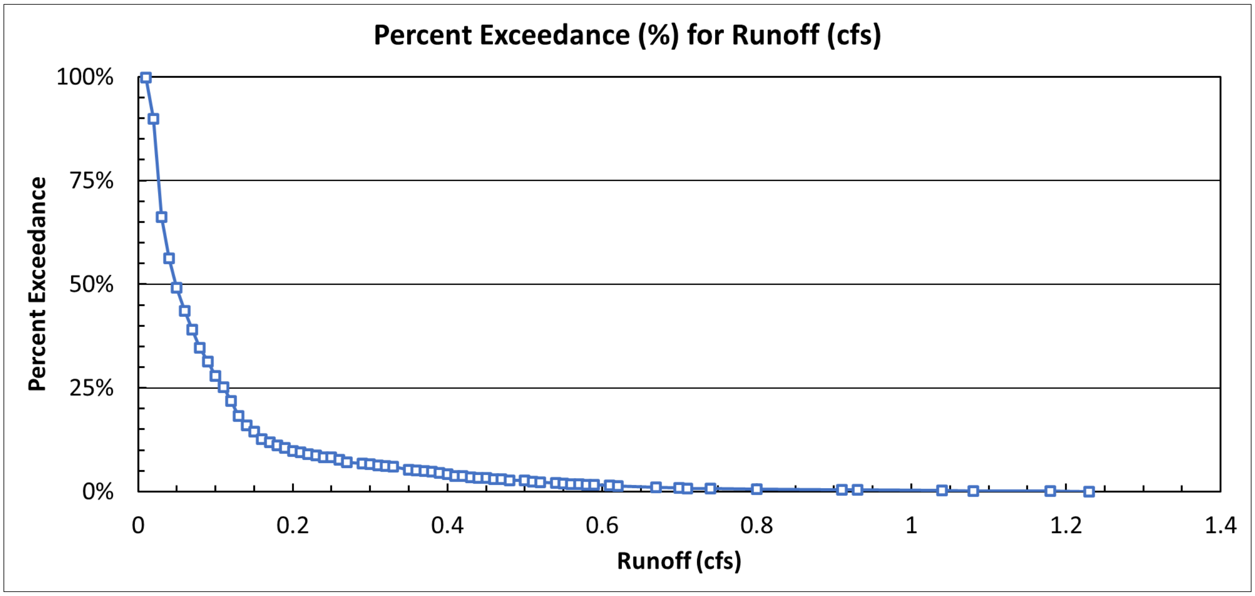

Figure 4. Percent exceedance for runoff data from an individual subcatchment within Miller Creek for the November 1998 through April 1999 period (n = 1023).

Approximately 50% of the simulated hourly runoff data is less than 0.05 cfs and 90% is less than 0.19 cfs. This logarithmic distribution of runoff data was separated into bins, which were used to analyze simulated concentration data for K and Ac as a function of small, medium, and large flow rate ranges. These data are shown in Figures 5-6 for K with an assumed toxicity limit of 0.13 g/L (130 mg/L) for K.

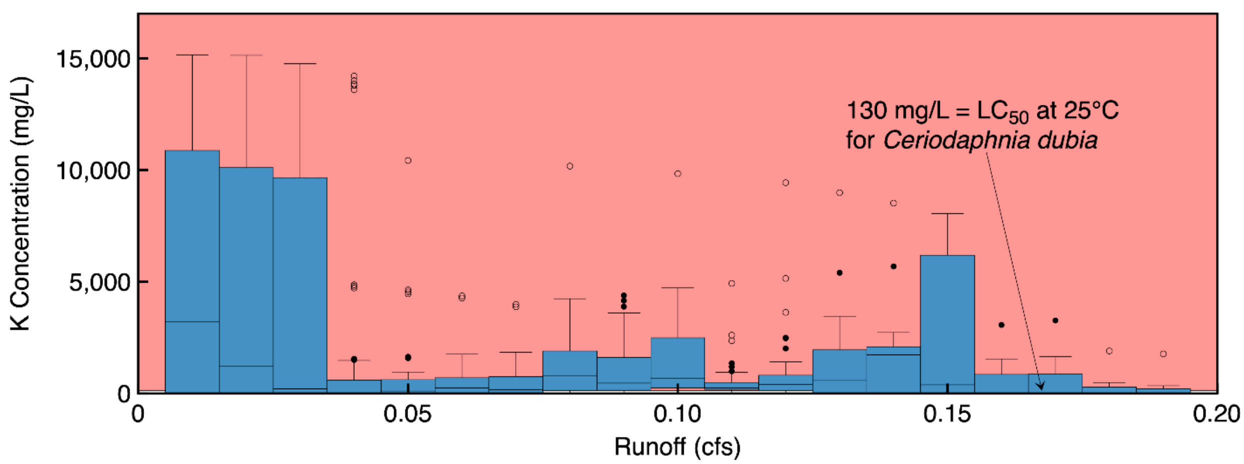

Figure 5. Potassium (K) concentration statistics for low flow rates (0 – 0.2 cfs) for an individual subcatchment as illustrated using box-and-whisker plots in which the center line is the median, the top and bottom of the boxes are the 75th and 25th percentiles, respectively, the whiskers are the interquartile range (IQR), outliers (within 1.5x beyond the IQR) are drawn as filled circles and extreme outliers (within 3x beyond the IQR) are open circles. A toxicity limit of 0.13 g/L for K was assumed and the region of concentration above this value is shaded in light red.

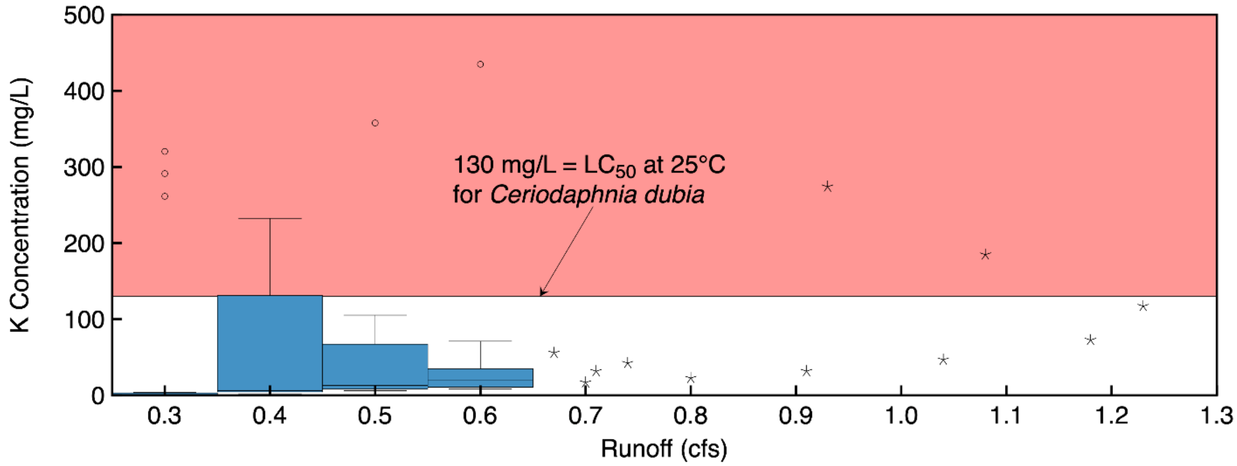

Figure 6. Potassium (K) concentration statistics for higher flow rates (0.3 – 1.3 cfs) for an individual subcatchment as illustrated using box-and-whisker plots in which the center line is the median, the top and bottom of the boxes are the 75th and 25th percentiles, respectively, the whiskers are the interquartile range (IQR), outliers (within 1.5x beyond the IQR) are drawn as filled circles and extreme outliers (within 3x beyond the IQR) are open circles. Individual flow rate values > 0.65 cfs are shown as asterisks (*). A toxicity limit of 0.13 g/L for K was assumed and the region of concentration above this value is shaded in light red.

For low flow rates (Q < 0.2 cfs, Figure 5), the concentration statistics for K range from 0 to over 15,000 mg/L. It is apparent from Figure 5 that the median values of K concentration exceed the assumed toxicity limit (130 mg/L) for nearly all the flow rates within this range. For high flows (0.2 cfs < Q < 1.3 cfs), the K concentration statistics range from 0 to ~250 mg/L for the interquartile range (IQR) and ~450 mg/L including extreme values. Only some extreme outliers (within 3x beyond the IQR) and individual hourly values for flow rates > 0.65 cfs (asterisks) exceed the assumed toxicity limit (130 mg/L) for the high flow rate range. It is also apparent from Figures 5 and 6 that the concentration 1) varies substantially as a function of flow rate, and 2) decreases from low flow rates to high flow rates.

Acetate (Ac) data for low flow rates (Q < 0.2 cfs, Figure 7) and high flow rates (0.2 cfs < Q < 1.3 cfs) are shown in Figures 7 and 8, respectively. The toxicity limit for Ac is assumed to be 7.26 g/L (7260 mg/L). Similar to K (Figures 5 and 6), Ac concentrations vary substantially as a function of flow rate and decrease from low flow rates to high flow rates as shown in Figures 7 and 8. Though the assumed toxicity limit for Ac is substantially larger than that for K (7260 mg/L vs. 130 mg/L), the range of concentration values for low flow rates still exceed the toxicity limit below 0.03 cfs as shown in Figure 7. All Ac concentration values were below the assumed toxicity limit for high flow rates as shown in Figure 8.

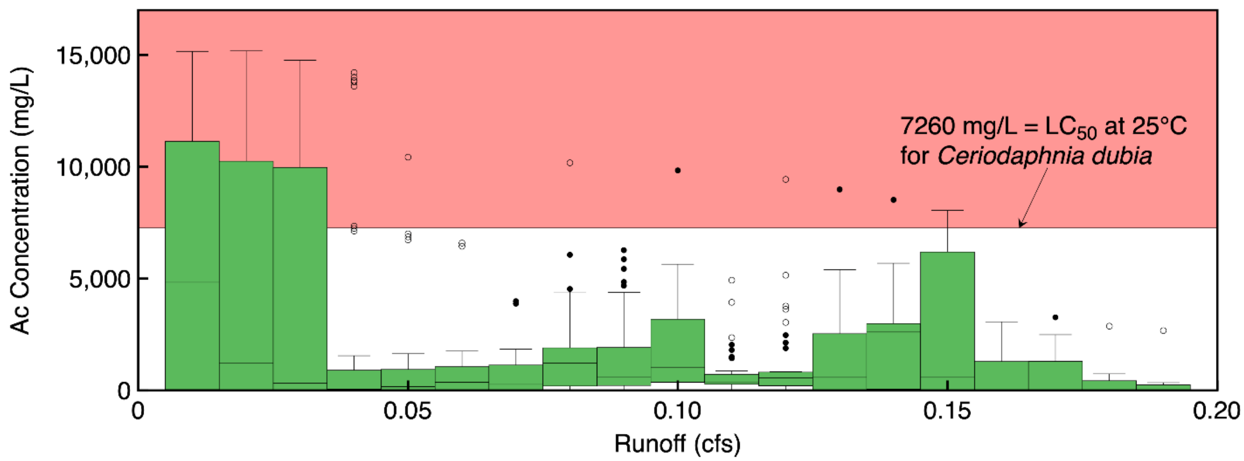

Figure 7. Acetate (Ac) concentration statistics for low flow rates (0 – 0.2 cfs) for an individual subcatchment as illustrated using box-and-whisker plots in which the center line is the median, the top and bottom of the boxes are the 75th and 25th percentiles, respectively, the whiskers are the interquartile range (IQR), outliers (within 1.5x beyond the IQR) are drawn as filled circles and extreme outliers (within 3x beyond the IQR) are open circles. A toxicity limit of 7.26 g/L for Ac was assumed and the region of concentration above this value is shaded in light red.

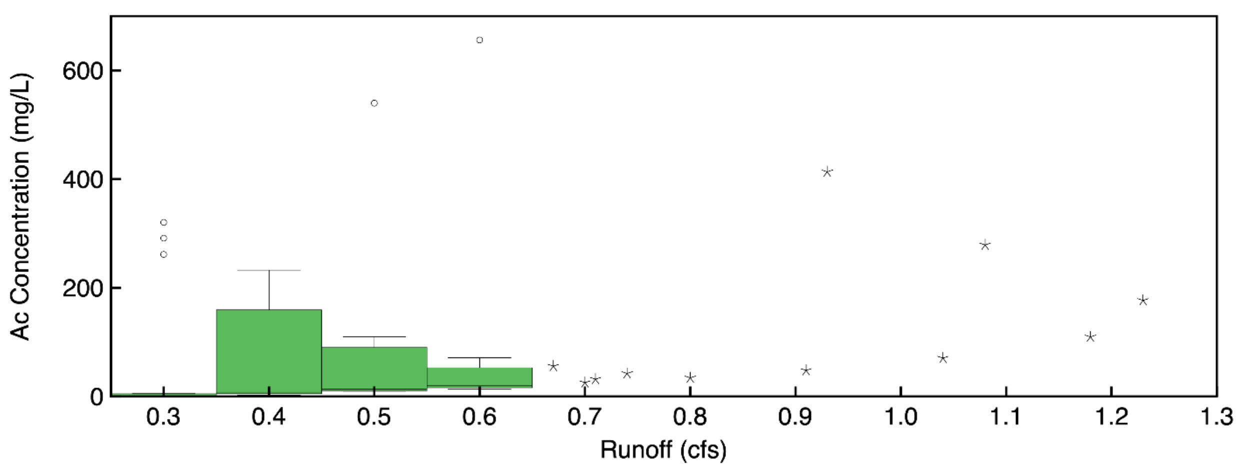

Figure 8. Acetate (Ac) concentration statistics for high flow rates (0.2 – 1.3 cfs) for an individual subcatchment as illustrated using box-and-whisker plots in which the center line is the median, the top and bottom of the boxes are the 75th and 25th percentiles, respectively, the whiskers are the interquartile range (IQR), outliers (within 1.5x beyond the IQR) are drawn as filled circles and extreme outliers (within 3x beyond the IQR) are open circles. Individual flow rate values > 0.65 cfs are shown as asterisks (*).

1.2 Runoff and Outflow Concentration from Miller Creek

The Miller Creek SWMM model was also run for the entire Miller Creek watershed under several scenarios, corresponding to different levels of KAc anti-icer usage in the watershed for the time period of November 1, 1998 to April 30, 1999:

- Case I) KAc used only on 25% of all roadways
- Case II) KAc used on all roadways
- Case III) KAc used on all roadways and parking lots (all paved areas in the watershed)

The flow rate at the outlet of Miller Creek is substantially larger than outflow from an individual subwatershed as shown in Figure 9 for Cases I, II, and III. The flow duration curves for Cases I, II, and II are nearly identical: the range of flow rates is 0 to 268 cfs for all three cases, with 50% of the data less than ~1.1 cfs and 90% of the data less than 27 cfs.

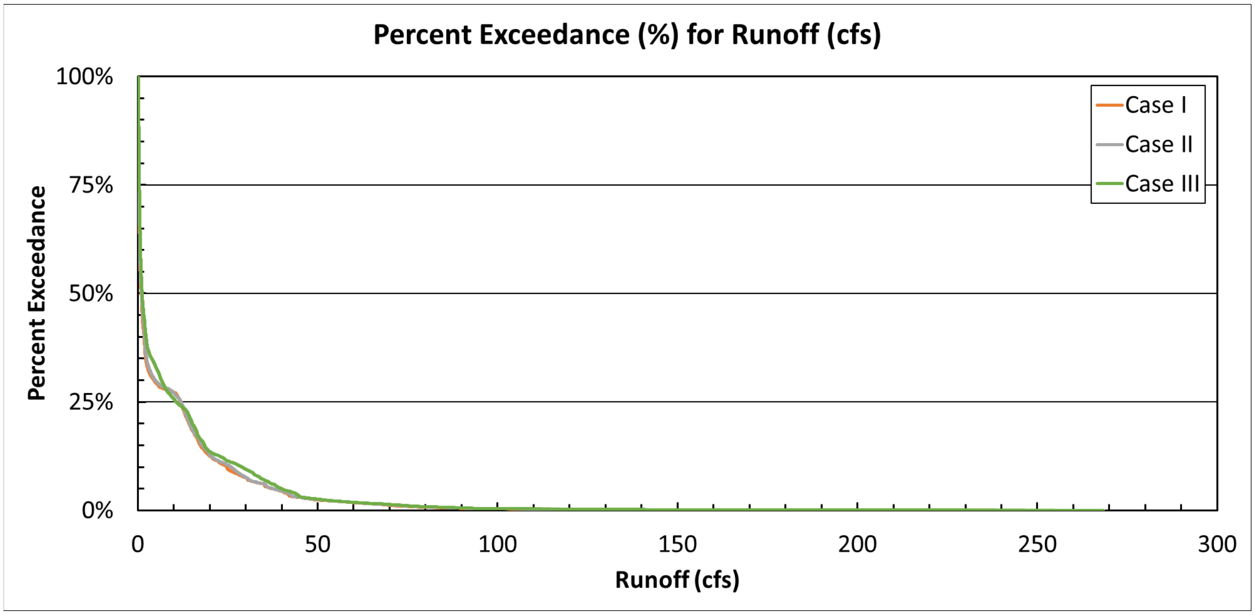

Figure 9. Percent exceedance for simulated non-zero outflow data from Miller Creek for Cases I, II, and III.

When KAc is used only on 25% of all roadways (Case I), the export of K and Ac from Miller Creek at the outlet is hypothesized to be less than the outflow concentration from an individual subcatchment (see section 3.2.1 above) and less than Cases II and III. Dilution within Miller Creek due to baseflow and by contributions from subcatchments with fewer roads and therefore lower KAc application will further dilute the concentration exported from Miller Creek at the outflow.

The simulated concentration of K in the outflow from Miller Creek for Cases I, II, and III for low flows (Q < 10 cfs) are shown in Figure 10, where flow rates are binned by unit cfs values. As expected, the increase in impermeable areas that receive KAc treatment results in an increase in K concentration in the outflow from Miller Creek, as evidenced by the increase in concentration statistics for Cases I, II, and III respectively (Figure 10). For Case I, only the interquartile range (IQR) and outliers for the lowest flow rate exceed the assumed toxicity limit of 130 mg/L for K (Figure 10). For Case II, more simulated concentration values at the lowest flow rate exceed the assumed toxicity limit for the low flows. For Case III, some median concentration values exceed the assumed toxicity limit through the entire range of 0 – 10 cfs flows.

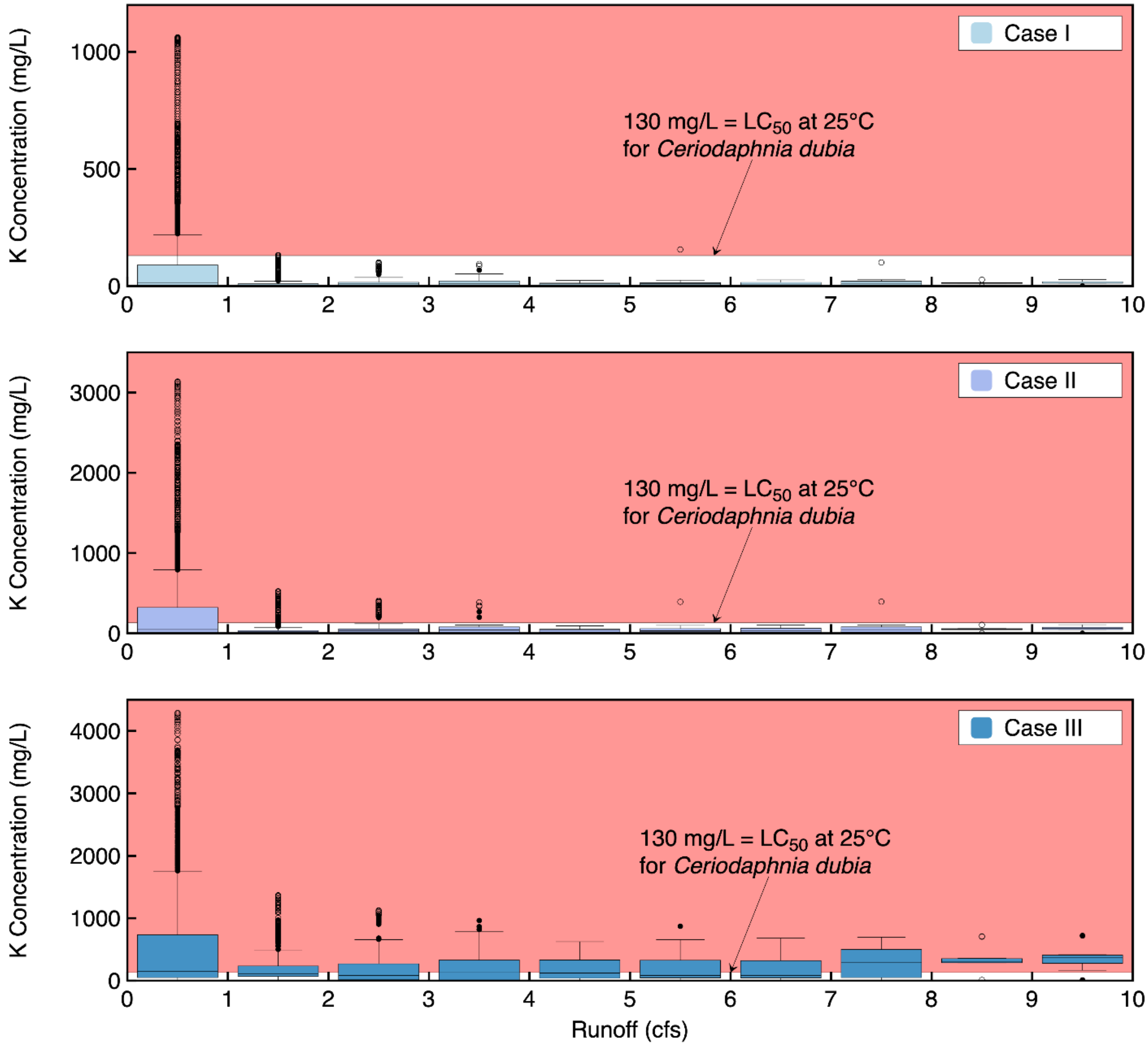

Figure 10. Potassium (K) outflow concentration statistics for low flow rates (0 – 10 cfs) for Case I (top), II (middle), and III (bottom) of Miller Creek as illustrated using box-and-whisker plots in which the center line is the median, the top and bottom of the boxes are the 75th and 25th percentiles, respectively, the whiskers are the interquartile range (IQR), outliers (within 1.5x beyond the IQR) are drawn as filled circles and extreme outliers (within 3x beyond the IQR) are open circles. A toxicity limit of 130 mg/L for K was assumed and the region of concentration above this value is shaded in light red.

K Concentration statistics for Cases I, II, and III for medium flow rates (10 – 45 cfs) are shown in Figure 11, where flow rates are binned by unit cfs values. Similar to the low flows, the K concentration increases from Case I to Case II and from Case II to Case III. Compared to the low flows, the K concentrations for all three cases are less for medium flows, demonstrating a decrease in concentration as the flow rate increases. This is expected because higher flow rates indicate more runoff that is likely disproportionate to the amount of KAc applied to the roadways, resulting in more dilution as flow rate increases. Nonetheless, some interquartile ranges and median values exceed the assumed toxicity limit for medium flow rates in Cases II and III.

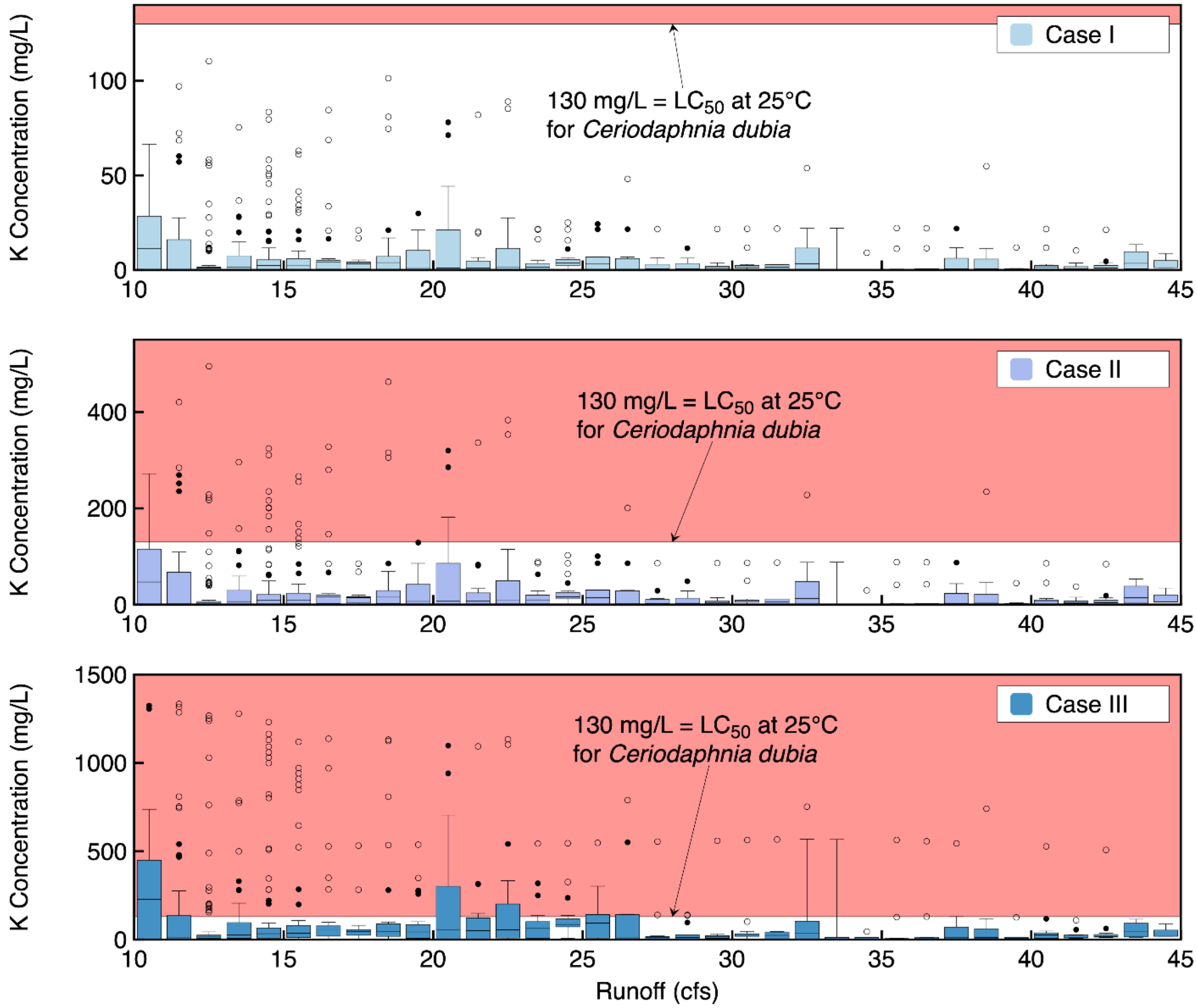

Figure 11. Potassium (K) outflow concentration statistics for medium flow rates (10 – 45 cfs) for Case I, II, and III of Miller Creek as illustrated using box-and-whisker plots in which the center line is the median, the top and bottom of the boxes are the 75th and 25th percentiles, respectively, the whiskers are the interquartile range (IQR), outliers (within 1.5x beyond the IQR) are drawn as filled circles and extreme outliers (within 3x beyond the IQR) are open circles. A toxicity limit of 130 mg/L for K was assumed and the region of concentration above this value is shaded in light red.

K Concentration statistics for Cases I, II, and III for high flow rates (45 – 280 cfs) are shown in Figure 12, where flow rates between 45 and 95 cfs are binned into 10 cfs groups. Similar to the low and medium flows, the K concentration increases from Case I to Case II and from Case II to Case III. High flows also exhibit less concentration compared to medium flow rates, further demonstrating a decrease in concentration as the flow rate increases. Despite the overall decrease in concentration range for the high flow rates, some interquartile range values exceed the assumed toxicity limit for high flow rates in Case III. All values of K concentration in the outflow from Miller Creek for Cases I and II at the high flow rates are below the assumed toxicity limit of 130 mg/L (Figure 12).

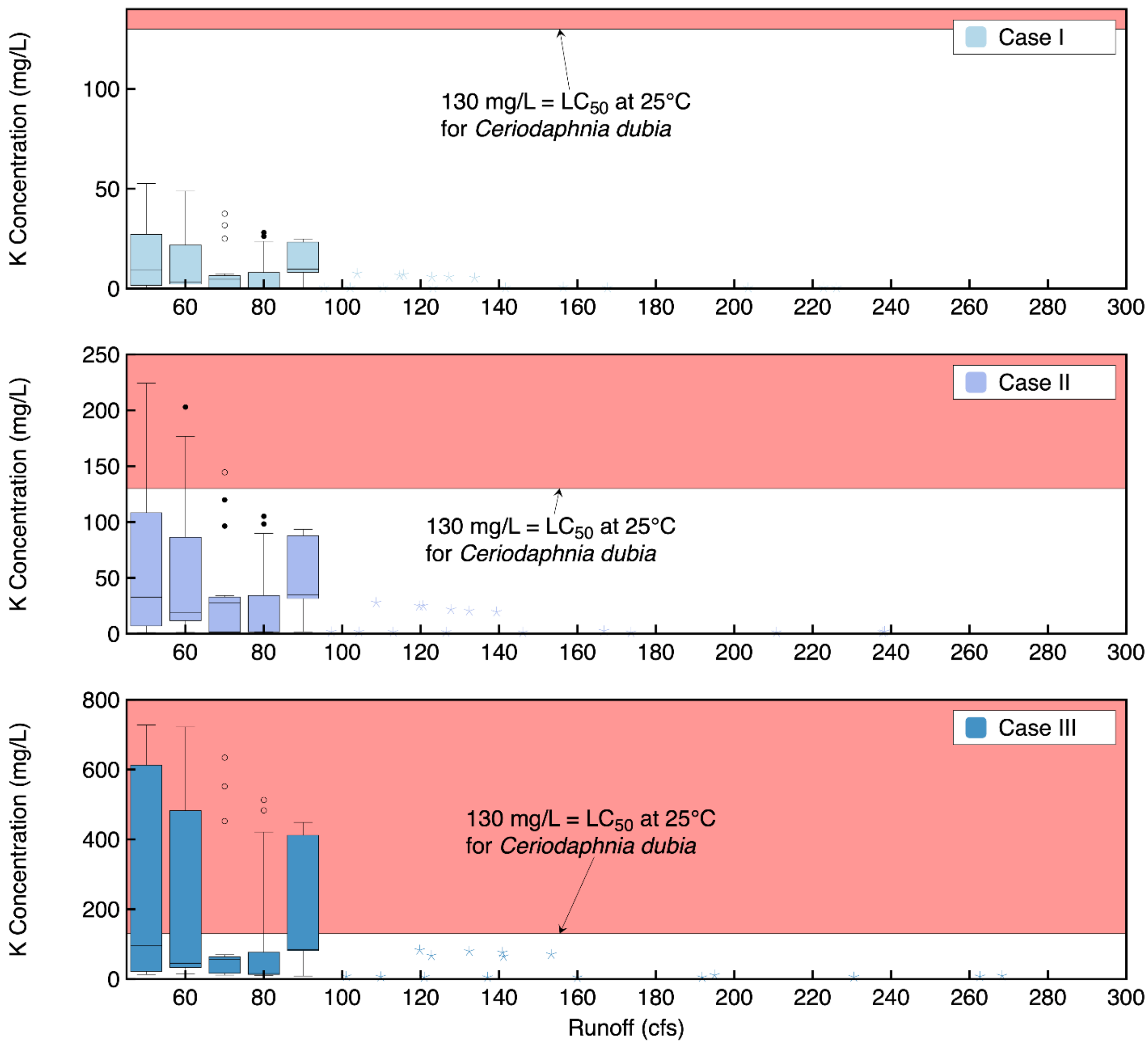

Figure 12. Potassium (K) outflow concentration statistics for high flow rates (45 – 270 cfs) for Case I, II, and III of Miller Creek as illustrated using box-and-whisker plots in which the center line is the median, the top and bottom of the boxes are the 75th and 25th percentiles, respectively, the whiskers are the interquartile range (IQR), outliers (within 1.5x beyond the IQR) are drawn as filled circles and extreme outliers (within 3x beyond the IQR) are open circles. Individual flow rate values > 95 cfs are shown as asterisks (*).

The simulated concentration of Ac in the outflow from Miller Creek for Cases I, II, and III for low flows (Q < 10 cfs) are shown in Figure 13, where flow rates are binned into unit cfs values. As expected, the increase in impermeable areas that receive KAc treatment results in an increase in Ac concentration in the outflow from Miller Creek, as evidenced by the increase in concentration statistics for Cases I, II, and III respectively (Figure 13). The toxicity limit for Ac is assumed to be 7,260 mg/L, but no low flow data exceeded this limit. Similar to K concentration data, Ac data decreases as flow rate increases and values for outflow from Miller Creek are substantially less than simulated values for an individual subcatchment (Figures 11 & 12).

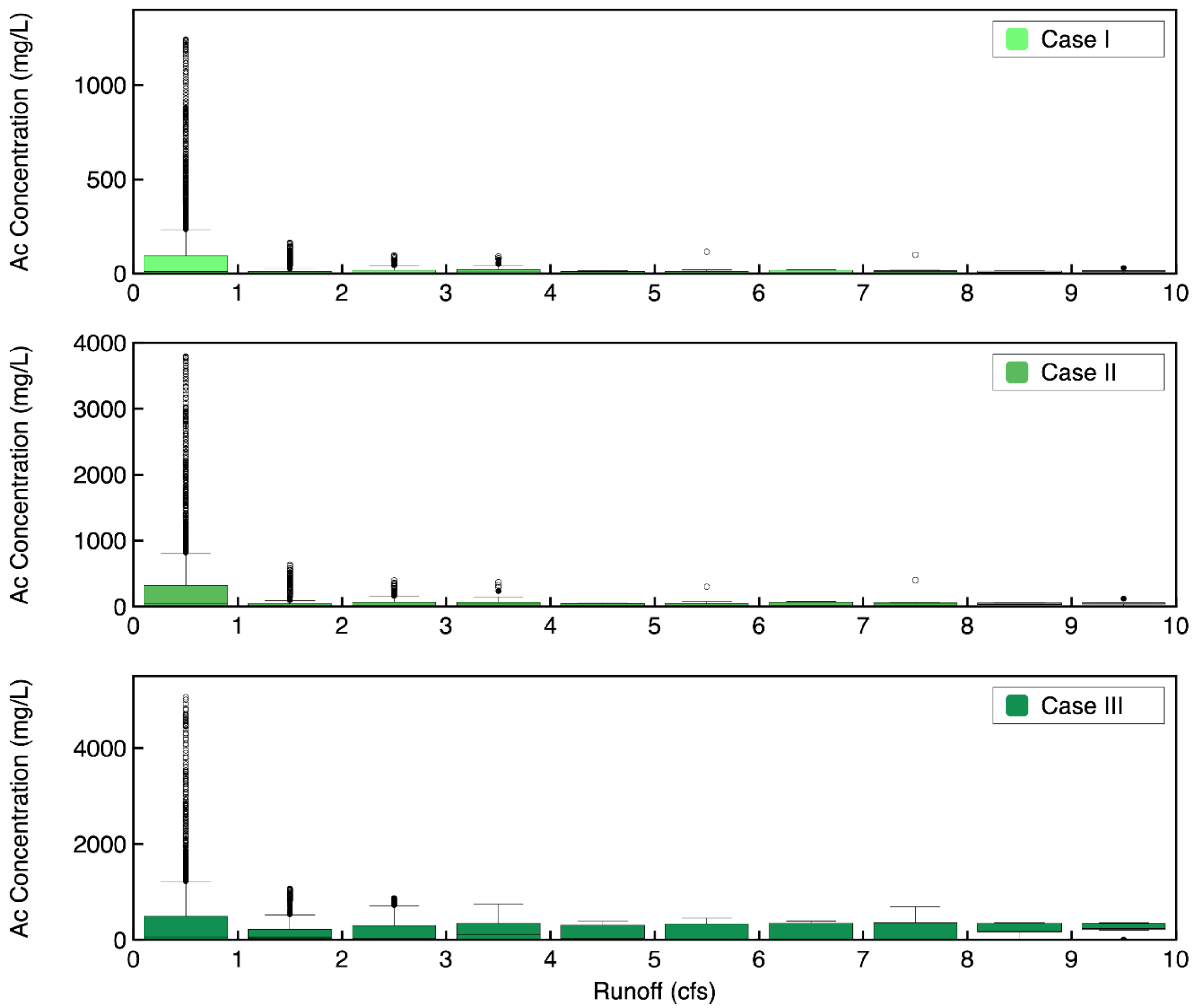

Figure 13. Acetate (Ac) outflow concentration statistics for low flow rates (0 – 10 cfs) for Case I, II, and III of Miller Creek as illustrated using box-and-whisker plots in which the center line is the median, the top and bottom of the boxes are the 75th and 25th percentiles, respectively, the whiskers are the interquartile range (IQR), outliers (within 1.5x beyond the IQR) are drawn as filled circles and extreme outliers (within 3x beyond the IQR) are open circles.

Ac concentration statistics for Cases I, II, and III for medium flow rates (10 – 45 cfs) are shown in Figure 14, where flow rates are binned into unit cfs values. Similar to the low flows, the Ac concentration increases from Case I to Case II and from Case II to Case III. Compared to the low flows, the Ac concentrations for all three cases are less for medium flows, demonstrating a decrease in concentration as the flow rate increases. While all Ac concentration values are below the toxicity limit, it is still apparent that the difference in application rates between Cases I, II, and III produces a substantial increase in Ac concentration in the outflow from Miller Creek.

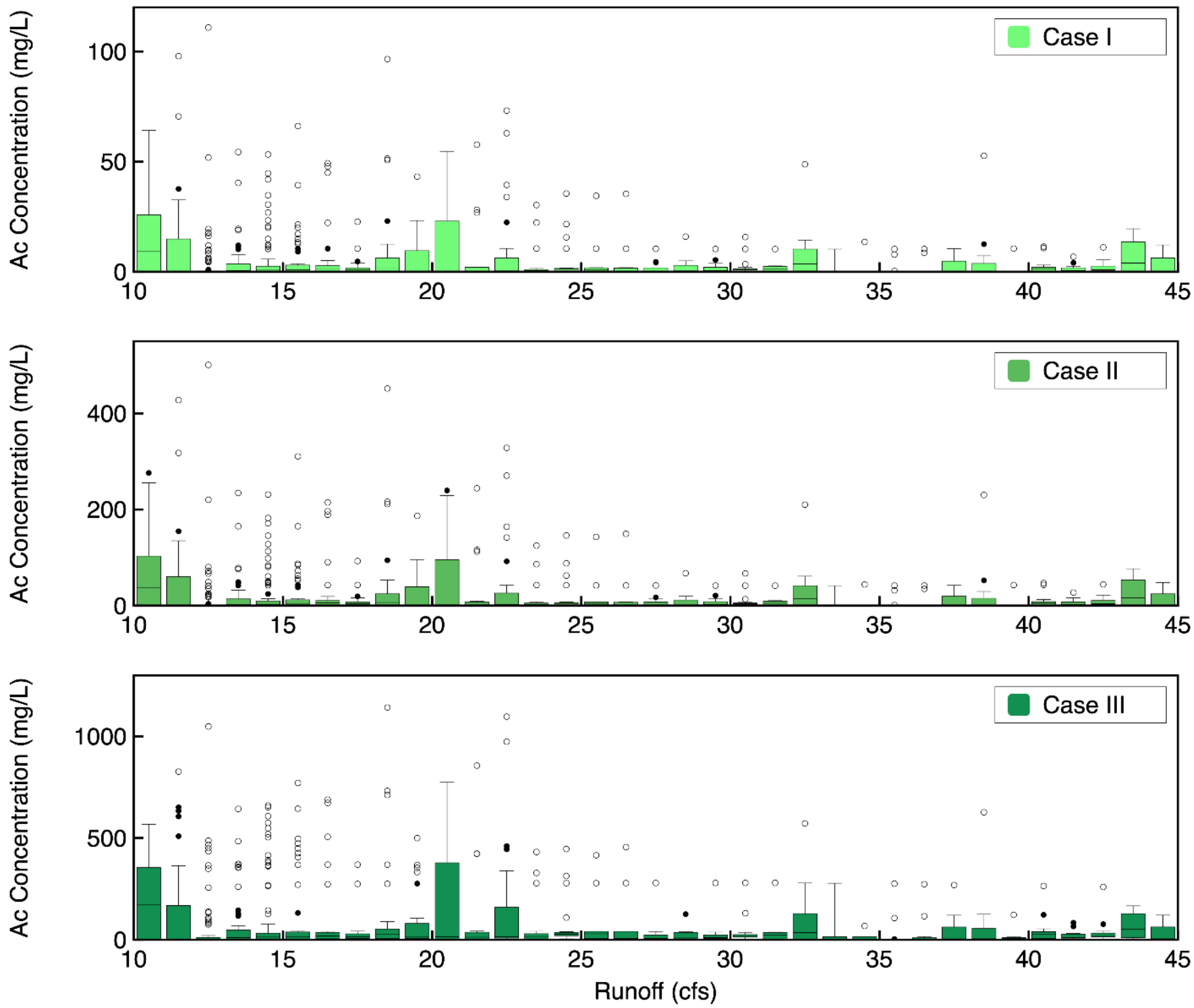

Figure 14. Acetate (Ac) outflow concentration statistics for medium flow rates (10 – 45 cfs) for Case I, II, and III of Miller Creek as illustrated using box-and-whisker plots in which the center line is the median, the top and bottom of the boxes are the 75th and 25th percentiles, respectively, the whiskers are the interquartile range (IQR), outliers (within 1.5x beyond the IQR) are drawn as filled circles and extreme outliers (within 3x beyond the IQR) are open circles.

Ac Concentration statistics for Cases I, II, and III for high flow rates (45 – 280 cfs) are shown in Figure 15, where flow rates between 45 and 95 cfs are binned into 10 cfs units. Similar to the low and medium flows, the Ac concentration increases from Case I to Case II and from Case II to Case III. High flows also exhibit less concentration compared to medium flow rates, further demonstrating a decrease in concentration as the flow rate increases. While all Ac concentration values are below the toxicity limit, high flow rates in combination with moderate Ac concentration could produce substantial Ac load delivered to downstream water bodies.

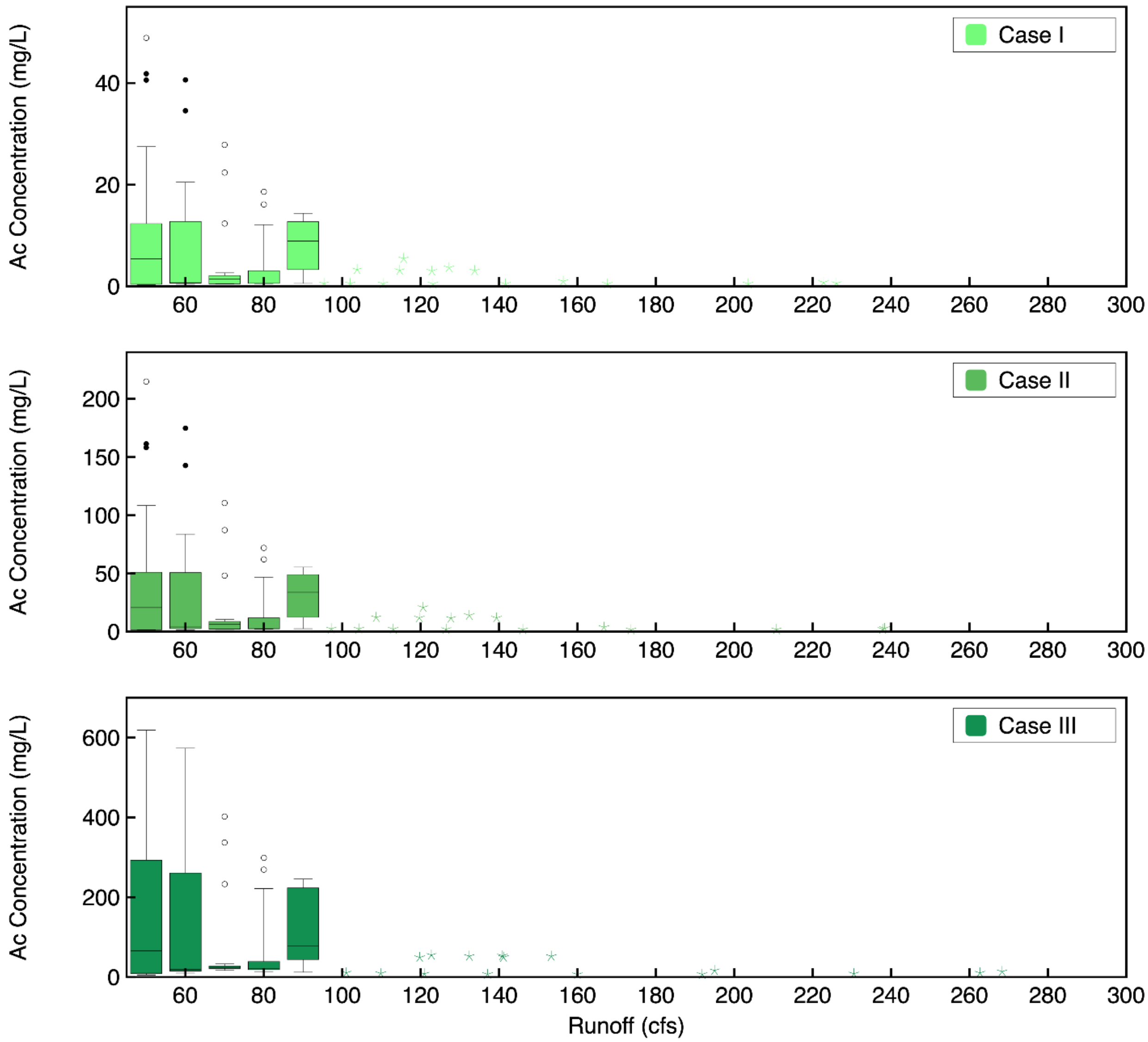

Figure 15. Acetate (Ac) outflow concentration statistics for high flow rates (45 – 270 cfs) for Case I, II, and III of Miller Creek as illustrated using box-and-whisker plots in which the center line is the median, the top and bottom of the boxes are the 75th and 25th percentiles, respectively, the whiskers are the interquartile range (IQR), outliers (within 1.5x beyond the IQR) are drawn as filled circles and extreme outliers (within 3x beyond the IQR) are open circles. Individual flow rate values > 95 cfs are shown as asterisks (*).

The de-icer concentration statistics for the Miller Creek outlet are summarized in Table 1. It is apparent from the difference in toxicity limit between Potassium (130 mg/L) and Acetate (7260 mg/L) that potassium will have more environmental impacts if the concentration of K and Ac are similar in magnitude. For K, the mean concentration exceeds the toxicity limit for Cases II and III, suggesting that less than 100% of the roadways can be treated with KAc without exceeding the toxicity limit. This is consistent with the data shown in Figures 10 – 12. The 90th percentile and max K concentrations exceed the toxicity limit for all three Cases, suggesting that even when limited to 25% of the roadways, there is still potential for environmental impacts of potassium.

By contrast, Acetate does not exceed the toxicity limit in the mean, 90th percentile, or maximum concentration for any of the three cases at the outlet of Miller Creek. This is consistent with the data shown in Figures 13 – 15. Thus, it is apparent that potassium has more potential for environmental impacts than acetate when considering toxicity. It is important to note, however, that acetate is an easily biodegradable substance and can create a substantial biological oxygen demand (BOD) impact on receiving waterbodies. This may become an issue of low dissolved oxygen if the acetate concentration is too high. Storm sewers, however, typically have a number of opportunities for reoxygenation (Huisman, et at. 2004), and the most likely impact would be in the downstream water body.

Table 1. Summary of Scenario Cases and Simulated Anti-icer Concentrations at the Miller Creek outlet. Anti-icer concentration statistics based on November 1, 1998 to April 30, 1999. All concentrations are mg/L. Values in bold italics exceed the assumed toxicity limit.

	Case I (25% of Roadways)	**Case II** (100% of All Roadways)	**Case III** (All Roadways and Parking Lots)
Total Connected Pavement Area Anti-iced (acres)	39.8	159.1	600.4
Potassium (K)			
Assumed K Toxicity Limit	130	130	130
Mean K Concentration	54.8	***171.1***	***334.3***
90^{th} Percentile K Concentration	***137.5***	***454.0***	***1034***
Max K Concentration	***1062***	***3136***	***4289***
Acetate (Ac)			
Assumed Ac Toxicity Limit	7260	7260	7260
Mean Ac Concentration	54.6	171.6	260.8
90^{th} Percentile Ac Concentration	137.5	489.8	711.7
Max Ac Concentration	1242.1	3790.9	5062.1

Time series of flow rate, K concentration, and Ac concentration for Case II are shown in Figure 16. The time series of flow rate, K, and Ac concentration are beneficial for illustrating the changes over time for these parameters at the outlet of Miller Creek. In Case II, 100% of the roadways are treated with KAc, which represents a median treatment strategy that could be employed by road maintenance crews. When comparing the K concentration to the K toxicity limit (130 mg/L), it is apparent that there are at least ten simulated events during the winter of 1998/99 in which the K toxicity limit was exceeded. Some events exceeded the toxicity limit by more than 10x. By contrast, the toxicity limit for Acetate is above the range for Figure 16 and thus is not exceeded during this simulated winter.

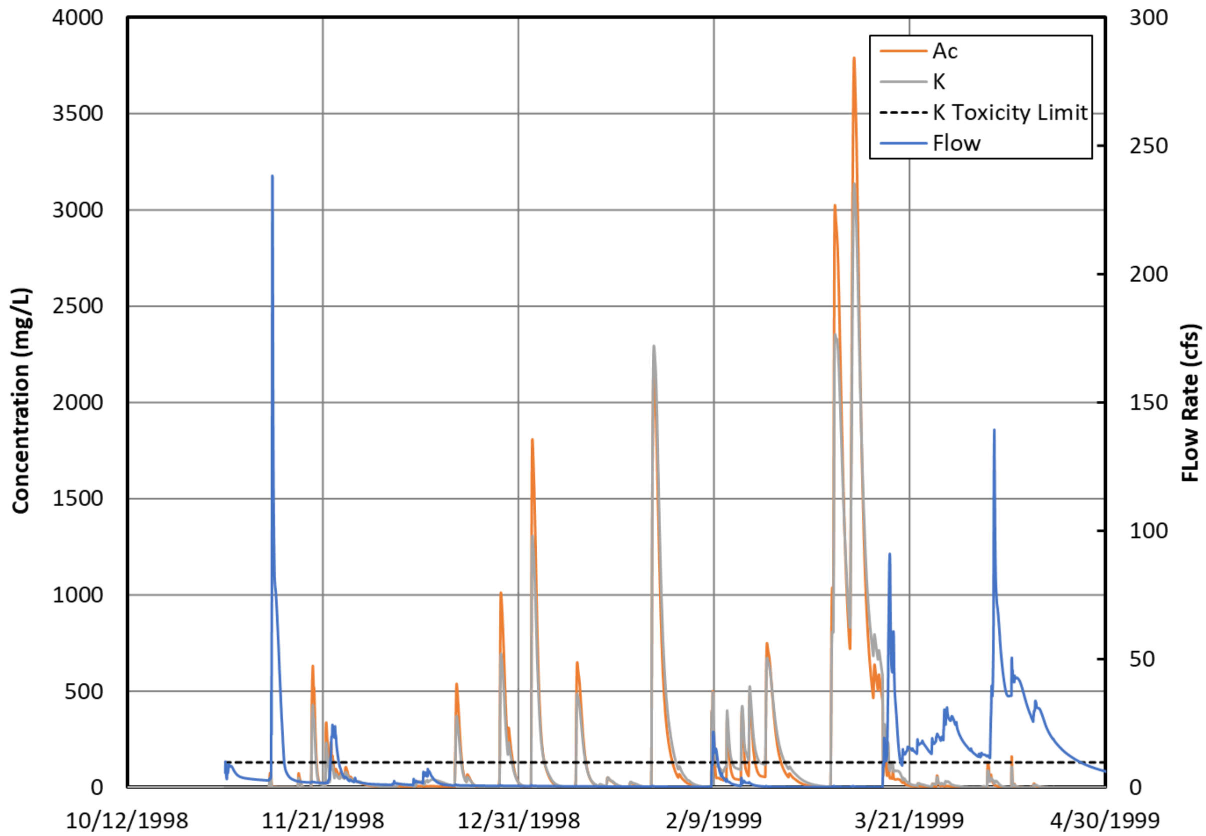

Figure 16. Simulated flow rate and K and Ac concentration at the outlet of Miller Creek for Case II (KAc applied to all roadways).

The time series of K concentration for the three cases are shown in Figure 17. This demonstrates the substantial differences in management strategies for Cases I, II, and III. Applying KAc on 25% of the roadways produces peak K concentrations of ~1150 mg/L. Increasing the application area to 100% of the roadways increases the peak K concentration to ~3150 mg/L and including the parking lots increases the peak K concentration to ~4300 mg/L. This is, however, for the highest concentration event. When considering the number of events, applying KAc on only 25% of the roadways produced only three events that exceeded the toxicity limit, whereas Case II (100% of roadways) produced at least ten events with exceedances. Including parking lots in Case III produced conditions in which the concentration did not drop below the toxicity limit between events, resulting in extended periods of time when the toxicity limit was exceeded. The environmental impacts of such conditions are substantial.

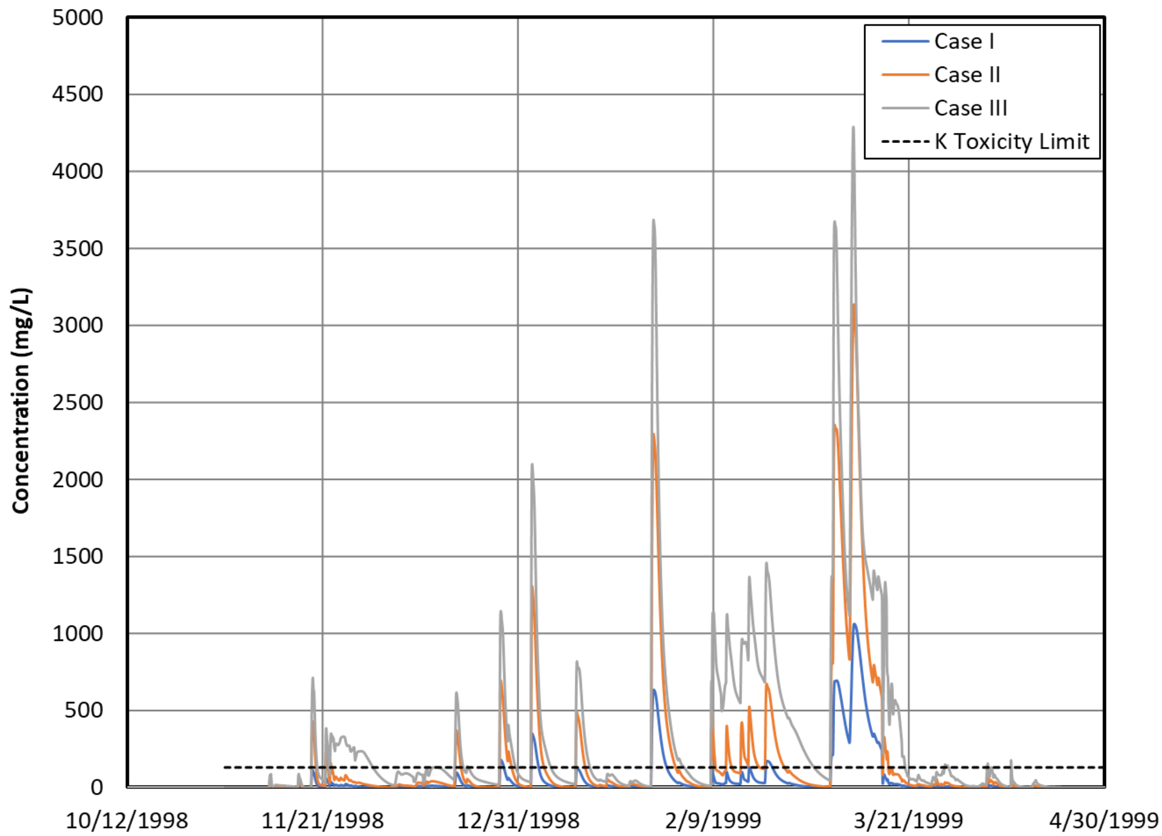

Figure 17. Simulated K concentration at the outlet of Miller Creek for Cases I, II, and III.

2 Preliminary Assessment

The K concentrations due to potassium acetate application as an anti-icer to 25% of the roads in the Miller Creek watershed were predicted to be above toxic concentrations for water fleas. Potassium, especially, is a chemical with a low LC_{50} and is a concern for the broad application of KAc anti-icer. We believe that KAc could be used in the most precarious winter driving safety locations, but not over all watershed roads or for all storms. Acetate could be used as a general organic anti-icer, but in combination with another cation, such as sodium or magnesium. These alternative ions do not, however, possess the low temperature effectiveness of KAc.

The results of this task focus on estimating concentrations of potassium acetate in surface waters, and do not consider the accumulation of potassium and acetate in roadside soils or in groundwater. The KAc in-stream concentrations simulated in this task assume that KAc is not transported through shallow groundwater, and therefore there is no background KAc concentration in baseflow. Some previous studies have shown, for example, relatively low degradation rates of acetate infiltrating to groundwater in winter conditions of 0.02 per day. Thus, it is possible that some acetate could appear in baseflow. If, however, the acetate concentration is similar to or lower than current chloride concentration in baseflow, it is not expected to cause impairments or toxicity exceedances.

It is important to note that the results given in this update are based on an analysis of the Miller Creek watershed in Duluth, MN. Other watersheds with similar climate conditions, watershed response to precipitation, and application rates of deicers and anti-icers are expected to have similar results.

Further work is needed in other parts of the state to extend and generalize the results for different climate regions and watershed characteristics.

Final Update June 30, 2022

The literature review (Activity 1) describes previous and recent literature on road salt alternatives, including chemicals (e.g., acetate, formate, glycol, glycerol) and abrasives (e.g., sand, heated sand) and the Seventh Update (January 31, 2022) for Activity 2 shared a thorough analysis of environmental impacts of potassium acetate as one road salt alternative. These results can be extended to represent other chemicals and for other watersheds or locations (given some assumptions) by considering the following differences:

1. Varying climate regime for other locations and watersheds,
2. Varying application rates for the chemicals,
3. Varying decay rate coefficients for organic chemicals, and
4. Varying toxicity thresholds for the chemicals being considered.

The best approach for assessing environmental impacts is for end users to choose the conditions for which they want the environmental impacts and model those conditions specifically, following the example established by this research project. Modeling every combination of toxicity, decay rate, application rate, and climate regime for all road alternatives and climate regimes in Minnesota is beyond the scope of this work. The following sections outline how these conditions vary and how the results can be interpreted to ascertain environmental impacts of various chemicals under various conditions.

Varying Climate Regimes for other Locations and Watersheds

Miller Creek in Duluth, MN was used as the primary study site for analyzing de-icer/anti-icer concentrations in surface runoff. To check if the Miller Creek results are representative of other areas of the state, snow fall data for Brainerd, Duluth, Minneapolis, and Rochester, MN were analyzed. For the 30-year period 1991-2020, Duluth received significantly more snowfall, on average, compared to Brainerd, Minneapolis and Rochester, and more days with 1 inch or greater snowfall (Figure 18). The median (50^{th} percentile) snowfall depth for Duluth was 90.2 inches, compared to 46, 52.7, and 47.4 inches for Brainerd, Minneapolis, and Rochester, respectively.

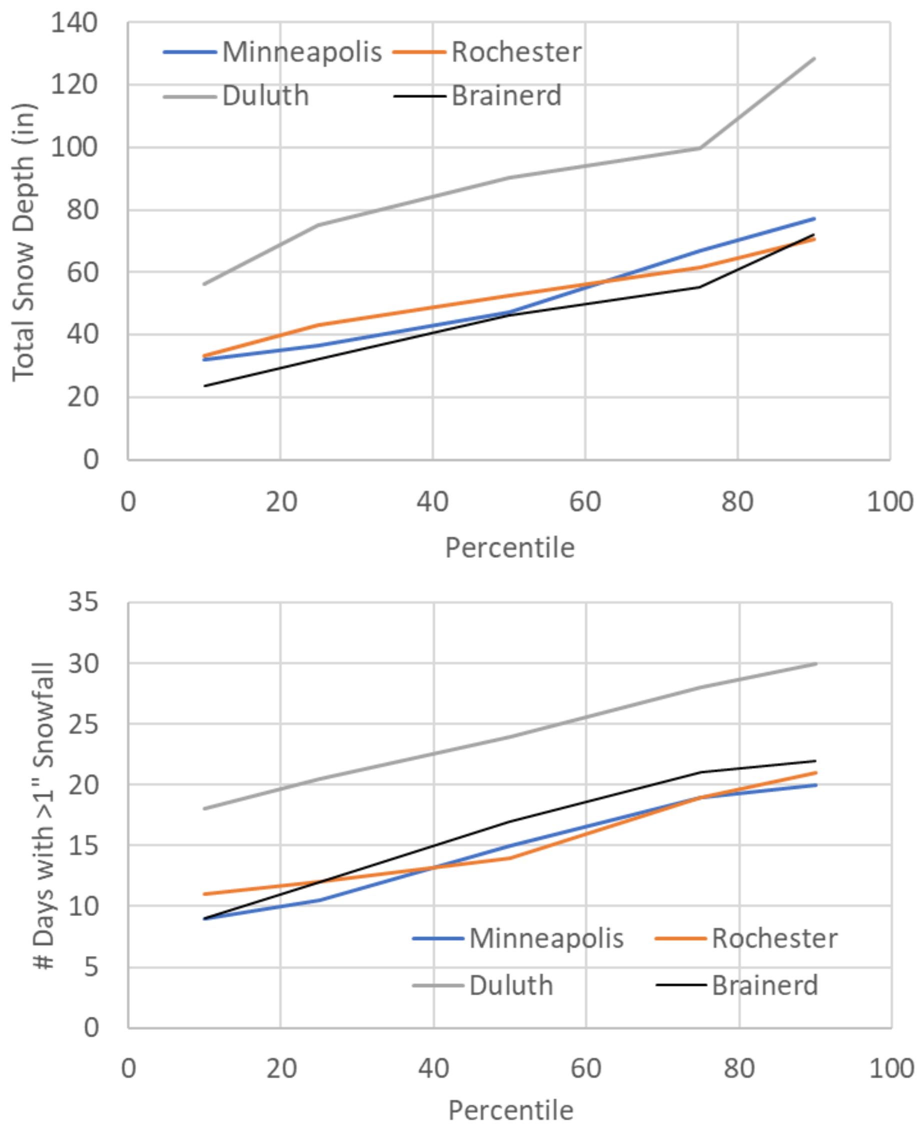

Figure 18. Statistics of total snowfall (upper panel) and number of days with at least 1 inch of snowfall (lower panel) for the winter seasons (October – April) from 1991-2020, for Brainerd, Duluth, Minneapolis, and Rochester.

To examine whether these differences in snowfall lead to significant differences in de-icer/anti-icer concentrations in surface runoff, 31 years of climate data (1990-2020) for Duluth and Minneapolis were used as input to the Miller Creek SWMM model to simulate 30 winter seasons. As before, potassium acetate was applied to the roadways on each day with at least one inch of snowfall. The SWMM model was run for a 31-year continuous simulation between January 1, 1990 and December 31, 2020 for each city. Simulated runoff and the concentrations of potassium and acetate were compiled for the outlet of Miller Creek for 30 winter seasons, starting with October 1, 1990 through April 30, 1991 and ending with October 1, 2019 through April 30, 2020. The simulation results for Duluth and Minneapolis are summarized in Table 2 and Figure 19. Although both snowfall and anti-icer application were higher for Duluth, the concentrations of anti-icer in surface runoff were similar for Minneapolis and Duluth (Table 2), suggesting that the larger snowfall depth in Duluth dilutes the higher total anti-icer application. However, 60% higher total application of anti-icer in Duluth compared to Minneapolis (Table 2) would lead to correspondingly higher total loading of anti-icers to downstream water bodies.

Year-to-year variability of the mean concentration in runoff is high at both sites (Figure 19). The year-to-year mean anti-icer concentration was found to be correlated to mean flow rate (r^2=0.87) at both sites, with similar inverse relationships (Figure 20). Higher flow rates tend to dilute the anti-icer concentrations, with an order of magnitude change in both flow rates and concentration over the 30 winter seasons.

Table 2. Summary of SWMM simulation results for runoff concentrations of potassium and acetate over 30 winter seasons (1990-91 to 2019-20) in Duluth and Minneapolis, MN. Mean concentrations are flow-weighted.

Variable	Duluth	Minneapolis
Flow Rate, Mean (cfs)	5.2	3.4
Acetate, Total Application per Winter, Mean (kg)	6890	4223
Acetate Conc., Mean (mg/L)	37.8	41.7
Acetate Conc., Max (mg/L)	2794	2183
Potassium, Total Application per Winter, Mean (kg)	4570	2799
Potassium Conc., Mean (mg/L)	39.0	42.6
Potassium Conc., Max (mg/L)	2573	1893

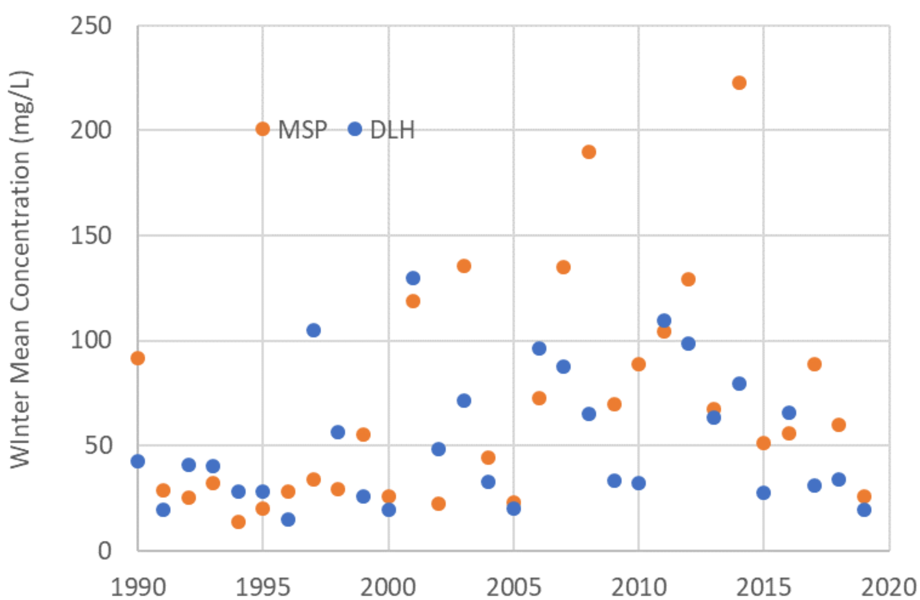

Figure 19. Simulated flow-weighted mean acetate concentration for each winter season (1990-91 to 2019-20) in Minneapolis and Duluth.

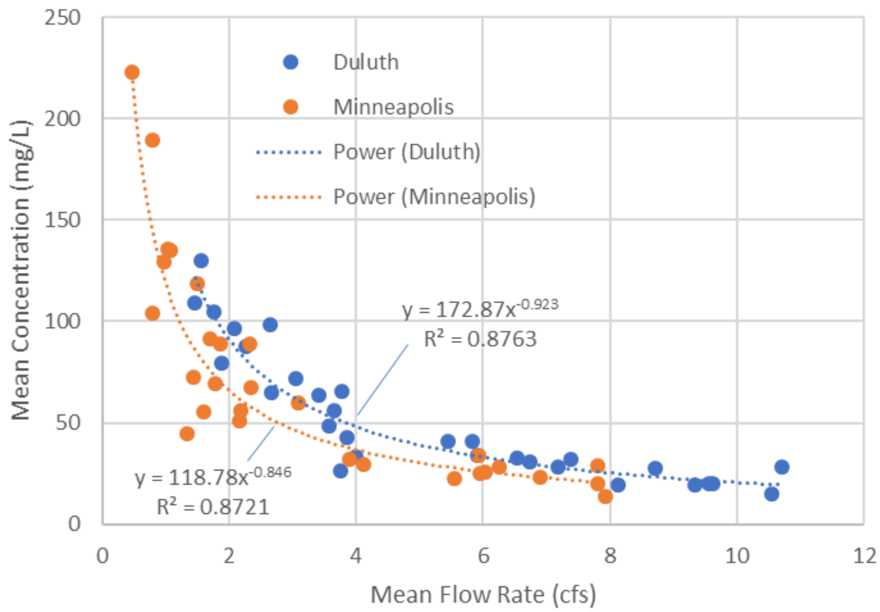

Figure 20. Relationship between flow-weighted annual mean acetate concentration and annual mean flow rate for 30 winter seasons in Minneapolis and Duluth, MN.

Varying Application Rates

More details and the ranges of the application rates for various road salt alternative chemicals is provided in the literature review (Activity 1), but Table 3 below provides a summary for several chemicals. For comparison, the modeling described in the previous status update assumed Potassium Acetate application as liquid at 42.5 gal/lane mile.

Table 3. Summary of Application rates for various road salt alternatives.

Road Salt Alternative	**Application Rate**	**Reference**
Sodium Acetate (NaAc)	190-320 lbs/lane-mile when near 32°F.	Fay et al. 2015
	600-1500 lbs/lane-mile at 10°F (1" of ice)	
Calcium Magnesium Acetate (CMA)	250-400 lbs/lane-mile	
Potassium Acetate (Kac)	25-60 gal/lane-mile as an anti-icer, 60-80 gal/lane mile as deicer	
Sodium Formate (NaFo)	125-250 lb/lane-mile near 32°F and thin ice, 400-1000 lb/lane-mile at 10°F and 1" ice.	
Potassium Formate (KFo)		
Ethylene Glycol	50-2000 gal/lane mile	
Propylene Glycol		
SnowMelt (a fully bio-based product), Fusion (a mixture of a bio-based product and chloride salt), and Caliber M1000 (another mix of a bio-based product and chloride)	3, 6, 9 liters per 1000 ft^2	Hosseini et al. 2017
Sodium Chloride (NaCl) and liquid Potassium Succinate (KSu)	Typical anti-icing application rates used by state DOTs range from 40 to 75 gal/lane-mile.	Fay and Akin 2018

Fay, L., Honarvarnazari, M., Jungwirth, S., Muthumani, A., Cui, N., Shi, X., Bergner, D., Venner, M. 2015. Manual of Environmental Best Practices for Snow and Ice Control. Clear Roads and Minnesota DOT.

Fay, L., and M. Akin, 2018. Investigation of Alternative Deicers for Snow and Ice Control, Center for Environmentally Sustainable Transportation in Cold Climates, University of Alaska Fairbanks, Fairbanks, AK, USA.

Hosseini, F., Hossain, S.M.K., and L.P. Fu, 2017. Bio-based materials for improving winter pavement friction, Canadian Journal of Civil Engineering, 44(2):99-105.

In general, most road salt alternative chemicals are applied at rates greater than 42.5 gal/lane-mile. Thus, assuming similar decay rates and other modeling parameters as described above, one could assume that road salt alternatives applied at greater rates will produce greater acetate outflow concentrations compared to the results displayed in the Seventh Update (January 31, 2022) for Activity 2.

Varying Decay Rate Coefficients

Organic compounds such as acetate, formate, glycol and glycerol will experience natural biodegradation during transport in the environment. This was modeled within EPA-SWMM using the built-in first order decay rate equation. Values for first-order decay coefficient (k) will depend on temperature and compound, though EPA SWMM guidance recommends 0.11 per day (US EPA 2016) for general modeling of biochemical oxygen demand (BOD) processes such as this. This assumes, however, normal summer temperatures (~20°C), which are not appropriate for winter and spring conditions during which organic road salt alternatives will be transported through the environment. In the modeling described in the Seventh Update (January 31, 2022) for Activity 2, acetate was assigned a decay coefficient (k) of 0.03 per day based on values measured at 34°F, 39°F, and 46°F (1°C, 4°C, and 8 °C) (Revitt and Worrall, 2003). Little information is available for organic road salt alternatives at low temperatures, but this value is likely appropriate for formate, glycol and glycerol in addition to acetate. For accurate environmental impact assessments, however, biodegradation rates should be measured for the chemicals of interest and the temperatures at which they will be transported through the environment after anti-icing or de-icing application.

Revitt, D. M., & Worrall, P (2003). Low temperature biodegradation of airport de-icing fluids. Water Science and Technology, 48(9), 103–111.

U.S. Environmental Protection Agency. (2016). Storm water management model reference manual. Volume III – water quality. Retrieved from https://www.epa.gov/water-research/storm-water-management-model-swmm

Varying Toxicity Thresholds

The environmental impacts and toxicity considerations for Calcium Magnesium Acetate (CMA) include 2500 mg/L to 3000 mg/L does not affect plant growth directly but may be deadly to seedlings (Horner 1988). A concentration of 5000 mg/L of CMA was found to slightly delay the hatching of rainbow trout but it did not affect the number of eggs hatched (Winters et al. 1984). Water flea reproduction was significantly inhibited at 250 mg/L CMA but there was no harmful impact to algae at concentrations under 50 mg/L CMA (Winters et al. 1984).

Though no numeric values were given, Ice-B-Gone (pellet form of CMA) was found to have a low level of toxicity for acute oral toxicity, sub-chronic toxicity, acute inhalation toxicity, acute dermal toxicity, skin irritation, eye irritation, and skin sensitization when tests were performed on rats and the latter two tests were also performed on human volunteers (Buteau et al 1992). CMA was found to be a slight eye irritant but not a skin irritant or skin sensitizer.

Goldman and Lubnow (1992) found that concentrations of 10 mg/L CMA appeared to increase chlorophyll in one lake and a concentration of 1 mg/L resulted in statistically higher chlorophyll concentrations in another lake. During the summer, eight out of the ten lakes showed no response to CMA at doses of 0.1, 1.0, and 10 mg/L CMA but bioassays in the late spring and early winter showed slight responses to CMA.

Joutti et al. (2003) tested sodium chloride, calcium chloride, magnesium chloride, potassium formate, potassium acetate, and CMA with different bioassays. Bioassays were an onion plant root elongation test, a duckweed growth inhibition text, an enzyme inhibition test, and a microbial test (luminescent bacteria, BioTox test). Overall, the organic chemicals were more toxic than the inorganic salts. The rank of toxicity, according to the root elongation and growth inhibition tests, were, from most toxic to least toxic: potassium formate, potassium acetate, CMA, calcium chloride, sodium chloride, and magnesium chloride. CMA could not be tested for the other two bioassays due to the turbidity of the samples.

Dougherty and Smith (2006) investigated the effect of sodium chloride, magnesium chloride, calcium acetate, magnesium acetate, sodium ferrocyanide, and sodium formate on tadpoles of two frog species and one road species. Some salt compounds negatively affected some tadpoles but the acetates, sodium ferrocyanide, and sodium formate did not. All the concentrations tested were less than 170 mg/L and it was noted that higher concentrations may result in more of an impact.

Hanslin (2011) found that increasing concentrations from zero to 13.3 mmol/L soil caused negative responses, but results varied with five plant species investigated. Root growth decreased in two species and leaf biomass decreased in four of the five species. There was no impact on specific leaf area, relative chlorophyll content, height increase, or chlorophyll fluorescence. Overall, the organic deicers did not have less impact on saplings than sodium chloride did during active growth.

In summary, toxicity varies amongst chemicals and species. Thus, conditions must be chosen to determine the extent of environmental impacts. As described above, climate regime, application rate, and decay rate for organic chemicals will affect the concentration of road salt alternatives. When modeled appropriately and specifically for the chemicals of interest, then outflow concentrations can be compared to toxicity thresholds to determine what environmental impacts may occur, as exemplified by the modeling results described in the Seventh Update (January 31, 2022) for Activity 2.

ACTIVITY 3: Conduct friction tests on pavement cores to select promising techniques.
Description: Blocks of several different pavement types will be treated with approximately 12 road salt alternatives and pavement innovations, and exposed to typical winter conditions in a climate-controlled room. The temperature, humidity, and ice cover will be controlled to make direct comparisons between alternatives. One of several road friction testers will be selected for these experiments and used to measure road friction in simulated winter conditions with pavement innovations and road salt alternatives. Ranking metrics will be developed based on cost and environmental impact of the alternatives, as well as road friction results for various simulated winter conditions.

ENRTF BUDGET: $190,734

Outcome	Completion Date
1. Laboratory road friction tests completed in various conditions for road salt alternatives	12/31/2020
2. Develop ranking metrics from cost and predicted road friction results for all alternatives	3/31/2021
3. Write report on laboratory results	6/30/2021

First Update January 31, 2019

The project team has met several times to discuss the objectives and outcomes of the laboratory friction measurements. A preliminary plan and instrumentation for the measurements has been developed and a preliminary experimental procedure has been developed and tested. The measurements will commence in the next semi-annual period.

Second Update June 30, 2019

1. We've developed a novel protocol for measuring de-icing effectiveness of various road salt alternative chemicals related to skid resistance (friction) in laboratory conditions. The surface of the pavement is simulated by a special arrangement of cylindrical specimens that form a much larger area of testing on which a dynamic friction tester can effectively measure friction coefficient at various speeds and temperatures.
2. We have also developed a protocol for measuring anti-icing effect by measuring the shear strength (adhesion) of the interface between surfaces treated with various road salt alternatives and ice. A servo-hydraulic testing machine equipped with an environmental chamber and special fixtures were used for the testing.
3. The road salt alternatives currently under consideration include conventional salt (NaCl) as a baseline for comparison, Magnesium Chloride ($MgCl_2$), Potassium Acetate (KAc), CF7 (commercial KAc mix), Propylene Glycol (organic chemical), Abrasives (de-icing only), and Pavement Technologies (pending availability).

Third Update January 31, 2020

1. The measuring anti-icing effect protocol was further refined to improve the precision of the measurements. A more consistent application method was set in place in order to replicate the field application rate of the anti-icing chemicals.
2. Control samples without anti-icing treatment and samples treated with three anti-icing chemicals, conventional salt (NaCl), Magnesium Chloride ($MgCl_2$), and CF7 (commercial KAc mix) were prepared. All of them were tested at four temperatures: -5 °C, -15 °C, -25 °C, -35 °C.

Fourth Update June 30, 2020

Laboratory testing (Activity 3) consists of friction measurements for de-icing and friction enhancement (e.g., sand and grit) and anti-icing experiments which measure the ability of road salt and road salt alternatives to weaken the bond between ice and pavement. All anti-icing chemicals that were planned for testing (no treatment, Na-Cl-based brine, Magnesium Chloride, Potassium Acetate, RainX) have been tested at various temperatures (-15 °C, -25 °C, -35 °C). Friction measurements for de-icing and friction enhancement will resume in the next biennium (July – Dec 2020).

Fifth Update January 31, 2021

Experimental data collection for Laboratory testing (Activity 3) was completed, and data analysis is underway. Pending data analysis approval, Activity 3, Outcome 1 will be complete during this biennium (Jan – June 2021). Subsequent to completion of Outcome 1, Outcome 2 (develop ranking metrics) and Outcome 3 (write report) can then be completed.

Sixth Update June 30, 2021:

The experimental analysis and the data analysis are complete. We are currently writing up the results for the final report.

Seventh Update January 31, 2022:

Two manuscripts describing the results of Activity 3 have been prepared; one submitted for publication and a second manuscript that will be completed and submitted during this biennium.

Final Update June 30, 2022

Two manuscripts describing the results of Activity 3 have been prepared. One was previously submitted for publication and a second manuscript is drafted and will be submitted.

IV. DISSEMINATION:

Description: Dissemination and transfer of new knowledge and technology will be directed towards homeowners, practitioners, regulatory units of government, and other interested stakeholders. The project team has a long history of providing training and dissemination of science through the Water Resource Center, the Erosion and Stormwater Certification Program and the MN Road Salt Applicator training. Information learned in this study will be incorporated into this and other certification curricula. The team is well-equipped to communicate and disseminate results and outreach will occur through a variety of established formats. The results will be incorporated into MPCA chloride reduction programming and policy.

Knowledge transfer will also occur through written and electronic communication streams including St. Anthony Falls Laboratory's UPDATES, a stormwater research newsletter distributed to over 2,400 subscribers and the University of Minnesota Extension Water Resources News published 4-6 times per year. The team will also seek to include information in the Minnegram and Confluence newsletters, published by the Water Resources Center. In addition, one or more journal articles will be submitted for publication from the results of this project.

The team is also well-equipped to engage in dialogue and collaboration with public entities including watershed districts, municipalities, counties, universities, the Minnesota Cities Stormwater Coalition, and statewide entities working on stormwater management. Finally, the team is able to collaborate and communicate with researchers and educators across multiple campuses spread throughout the state.

First Update January 31, 2019

The project is currently in the data collection and measurement phase and thus no data or results are available for dissemination. However, the existence and intentions of the project have been communicated with stakeholders and target audiences (cities, homeowners, associations, etc.) and will continue throughout the project. The following presentations have discussed the project and preliminary results:

- https://twin-cities.umn.edu/news-events/umn-experts-winter-weather-driving

Second Update June 30, 2019

The project is currently in the data collection and measurement phase and thus no data or results are available for dissemination. However, the existence and intentions of the project have been communicated with stakeholders and target audiences (cities, homeowners, associations, etc.) and will continue throughout the project.

Third Update January 31, 2020

The project is currently in the data collection and measurement phase and thus no data or results are available for dissemination. However, the existence and intentions of the project have been communicated with stakeholders and target audiences (cities, homeowners, associations, etc.) and will continue throughout the project. The following presentations have discussed the project and preliminary results:

- October 24, 2019. Invited to present "Recent, in progress, and future research on salt pathways, pavements, water softening, and all things chloride." Oral Presentation. 20th Annual Minnesota Road Salt Symposium. Vadnais Heights, MN.

Fourth Update June 30, 2020

The project is currently in the data collection and measurement phase and thus no data or results are available for dissemination. However, the existence and intentions of the project have been communicated with stakeholders and target audiences (cities, homeowners, associations, etc.) and will continue throughout the project.

Fifth Update January 31, 2021

The project is currently in the data collection and measurement phase and thus no data or results are available for dissemination. However, the existence and intentions of the project have been communicated with stakeholders and target audiences (cities, homeowners, associations, etc.) and will continue throughout the project.

Sixth Update June 30, 2021:

The following presentations have discussed the project and preliminary results:

- August 4, 2021. Invited to present "How Anti-icing Chemicals Affect Ice Bonding to Pavement at Different Temperatures." Oral Presentation. 2021 Road Salt Symposium. Virtual.

Seventh Update January 31, 2022:

The following publications and presentations have discussed the project and preliminary results:

- January 9–13, 2022. Invited to present " Increasing Friction on Roadway Ice with Water Heated Sand." Poster Presentation. 2022 Transportation Research Board Annual Meeting. Washington, D.C. Road Salt Symposium. Virtual.
- Erickson, A., Turos, M., Weiss, P., Gulliver, J. and Marasteanu, M. (2022, submitted). "Increasing friction on roadway ice with water-heated sand."
- Erickson, A., Turos, M., Weiss, P., Gulliver, J. and Marasteanu, M. (2022, in preparation). Effectiveness of Organic Anti-Icing Alternatives.

Final Update June 30, 2022

The following publications and presentations have discussed the project and preliminary results:

- December 7, 2021. Interviewed for "Good Question: How Does Salt Melt Ice?" with Jeff Wagner, WCCO 10 o'clock news.
- February 17, 2022. Invited to present "Urban Stormwater Runoff Research: Innovating Practice to Improve Water Quality." Oral Presentation. MPCA Minnesota GreenCorps. Virtual.
- February 18, 2022. Invited to lead "St. Anthony Falls Laboratory; A tour for participants of 2022 IECA Annual Conference and Trade Show." Oral Tour. 2022 International Erosion Control Association 50th Annual Conference. Minneapolis, MN.
- April 19, 2022. Invited to lead "Urban Stormwater Runoff Management." Oral presentation with Poornima Natarajan. St. Anthony Falls Laboratory; A tour for UMN CSE Dean Andrew G. Alleyne. Minneapolis, MN.

- May 6, 2022. Invited to present "Urban Stormwater Runoff Management." Oral presentation with Poornima Natarajan. 2022 St. Anthony Falls Laboratory Research Retreat. Minneapolis, MN.
- May 19, 2022. Invited to lead "St. Anthony Falls Laboratory; A tour for MN GreenCorps Members." Oral tour. St. Anthony Falls Laboratory. Minneapolis, MN.
- June 8, 2022. Invited to lead "St. Anthony Falls Laboratory; A tour for MN Watershed Partners." Oral tour. St. Anthony Falls Laboratory. Minneapolis, MN.
- June 28, 2022. Invited to present "Stormwater Research in Minnesota" Oral presentation. 2022 Water Environment Federation (WEF) Stormwater Summit. Minneapolis, MN.
- Erickson, A., Turos, M., Weiss, P., Gulliver, J. and Marasteanu, M. (2022, in preparation). "Increasing friction on roadway ice with water-heated sand."
- Erickson, A., Turos, M., Weiss, P., Gulliver, J. and Marasteanu, M. (2022, in preparation). Effectiveness of Organic Anti-Icing Alternatives.

V. PROJECT BUDGET SUMMARY:

A. Preliminary ENRTF Budget Overview: See attached budget spreadsheet

Explanation of Use of Classified Staff: N/A

Total Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation:

Enter Total Estimated Personnel Hours: 5166	Divide by 2,080 = TOTAL FTE: 2.5

Total Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation:

Enter Total Estimated Personnel Hours: 930	Divide by 2,080 = TOTAL FTE: 0.45

B. Other Funds:
None.

VI. PROJECT PARTNERS:

A. Partners receiving ENRTF funding

Name	Title	Affiliation	Role
Peter T. Weiss	Professor	Valparaiso University	Visiting Professor to St. Anthony Falls Laboratory and subject matter expert.
Connie Fortin		Fortin Consulting	Subject matter expert.

B. Partners NOT receiving ENRTF funding

Name	Title	Affiliation	Role
Brooke Asleson	Water Pollution Prevention Coordinator	Minnesota Pollution Control Agency	State regulatory leadership coordinating issues related to the overall chloride management strategies underway at the MPCA

VII. LONG-TERM- IMPLEMENTATION AND FUNDING:

The long-term implementation of the results of this project includes the dissemination of lessons learned, as described in section IV above. In addition, the project team is soliciting the Clear Road program for funds to match this effort, which would allow the project team to expand the research with field measurements and experiments of road salt alternatives in natural winter conditions. The project team is also pursuing opportunities to collect friction measurements of roadway surface throughout Minnesota, to better understand the friction of various pavements during winter conditions with, and without road salt applications. The information gained from this project will propel these future endeavors towards a robust understanding of road safety in cold Minnesota winters that also protects the environment from harmful anti-icing and de-icing chemicals.

VIII. REPORTING REQUIREMENTS:

- The project is for 4 years, will begin on July 1, 2018, and end on June 30, 2022.
- Periodic project status update reports will be submitted January 31 and June 30 of each year.
- A final report and associated products will be submitted between June 30 and August 15, 2022.

IX. SEE ADDITIONAL WORK PLAN COMPONENTS:

A. Budget Spreadsheet

Attachment A:
Environment and Natural Resources Trust Fund
M.L. 2018 Budget Spreadsheet

Project Title: Investigation of Road Salt Alternatives and Pavement Innovations
Legal Citation: M.L. 2018, Chp. 214, Art. 4, Sec. 02, Subd. 04c
Project Manager: John S. Gulliver
Organization: University of Minnesota
College/Department/Division: St. Anthony Falls Laboratory
M.L. 2018 ENRTF Appropriation: $400,000 the second year is from the trust fund to the Board of Regents of the University of Minnesota to investigate road-salt alternatives and pavement innovations to reduce lake, stream, and groundwater degradation caused by road-salt chlorides. This appropriation is available until June 30, 2021, by which time the project must be completed and final products delivered.
Project Length and Completion Date: 4 Years ending June 30, 2022
Date of Report: August 15, 2022

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	Activity 1 Revised Budget 4/21/22	Amount Spent (2022/06/30)	Activity 1 Balance	Activity 2 Revised Budget 4/21/22	Amount Spent (2022/06/30)	Activity 2 Balance	Activity 3 Revised Budget 4/21/22	Amount Spent (2022/06/30)	Activity 3 Balance	TOTAL BUDGET	Total Amount Spent (2022/06/30)	TOTAL BALANCE
BUDGET ITEM												
Personnel (Wages and Benefits)												
Personnel: Professor (J. Gulliver), Supervisory and Analysis, 6.7% FTE (75% salary, 25% benefits) each year for 3 years. $58,835	$6,259	$6,259	$0	$28,189	$28,189	$0	$24,386	$24,386	$0	$58,834	$58,834	$0
Personnel: Professor (B. Wilson), Supervisory and Analysis, 1.9% FTE (75% salary, 25% benefits) each year for 3 years. $11,124	$0	$0	$0	$5,964	$5,964	$0	$5,160	$5,160	$0	$11,124	$11,124	$0
Personnel: Professor (M. Marasteanu), Supervisory and Analysis, 1.9% FTE (75% salary, 25% benefits) each year for 3 years. $16,896	$1,342	$1,342	$0	$6,042	$6,042	$0	$9,512	$9,512	$0	$16,896	$16,896	$0
Personnel: Research Associate (A. Erickson), Literature review, computer modeling, laboratory experiments, and analysis, 36% FTE (75% salary, 25% benefits) each year for 3 years. $176,976	$11,497	$11,497	$0	$51,778	$51,778	$0	$113,703	$113,703	$0	$176,978	$176,978	$0
Personnel: Research Associate (M. Turos), laboratory experiments and analysis, 16.7% FTE (75% salary, 25% benefits) each year for 3 years. $44,573	$4,781	$4,781	$0	$21,531	$21,531	$0	$18,261	$18,261	$0	$44,573	$44,573	$0
Personnel: Junior Engineer Trainee, Laboratory experiments, 4.8% FTE (100% salary) each year for 3 years. $2,534	$419	$419	$0	$1,885	$1,885	$0	$230	$230	$0	$2,534	$2,534	$0
Personnel: Junior Scientist (A. Ketchmark), Experimental apparatus and laboratory experiments, 15% FTE (79% salary, 21% benefits) each year for 3 years. $3,298	$3,298	$3,298	$0	$0	$0	$0	$0	$0	$0	$3,298	$3,298	$0
Professional/Technical/Service Contracts												
Professional/Technical/Service Contracts: Contract with Peter Weiss (Visiting Professor) to provide oversight and expertise with laboratory experiments. 10% FTE (100% salary) each year 3 years. $45,700	$0	$0	$0	$25,090	$25,090	$0	$20,610	$20,610	$0	$45,700	$45,700	$0
Professional/Technical/Service Contracts: Contract with Fortin Consulting to provide expertise and experience with data collection and analysis related to road salt alternatives. 4.8% FTE (100% Salary) each year for 3 years. $32,136	$0	$0	$0	$17,230	$17,230	$0	$14,905	$14,905	$0	$32,135	$32,135	$0
Lab analytical services. Analytical services to analyze road-side soil samples to compare the presence of sodium and chloride (conventional road salt) and soil properties that could be used to model breakdown of road salt alternatives such as organic chemicals. $6,058		$0	$0		$0	$0	$6,058	$6,058	$0	$6,058	$6,058	$0
Equipment/Tools/Supplies												
Equipment/Tools/Supplies: Supplies for experimental setup and analysis. $1,507		$0	$0		$0	$0	$1,507	$1,507	$0	$1,507	$1,507	$0
Capital Expenditures Over $5,000												
Printing												
Travel expenses in Minnesota												
Travel: Collect information and pavement cores. 500 miles @ $0.56/mi $363	$0	$0	$0	$363	$363	$0	$0	$0	$0	$363	$363	$0
COLUMN TOTAL	**$27,596**	**$27,596**	**$0**	**$158,072**	**$158,072**	**$0**	**$214,332**	**$214,332**	**$0**	**$400,000**	**$400,000**	**$0**